INTENSIVE CULTURE OF LOBLOLLY PINE (*Pinus taeda* L.) SEEDLINGS ON POORLY DRAINED SITES IN THE WESTERN GULF REGION OF THE UNITED STATES

A Dissertation

by

MOHD SHAFIQUR RAHMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2003

Major Subject: Forestry

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August 2003

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ABSTRACT

Intensive Culture of Loblolly Pine (*Pinus taeda* L.)
Seedlings on Poorly Drained Sites in the
Western Gulf Region of the United States. (August 2003)
Mohd Shafiqur Rahman, B. Sc., Chittagong University;
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A significant acreage of poorly drained sites occurs in the Western Gulf region of the United States. These sites experience standing water through much of the winter and spring, resulting in poor seedling survival. In addition, the sites occasionally experience a summer drought that affects tree growth. This study was designed to determine the effects of intensive forest management on seedling growth and physiology, and to enhance seedling performance under these harsh conditions. Fertilization, chemical vegetation control and mechanical site preparation were used in different combinations to test the effects of these intensive forest management tools on seedling above- and below-ground growth, survival, water status, gas exchange attributes, and nutrient concentrations in the foliage and soil solution. Ten sites were established in southern Arkansas in 1998 and 1999 to monitor loblolly pine (*Pinus taeda* L.) seedling performance in three consecutive growing seasons between 1998 and 2000.

Fertilization, chemical vegetation control and mechanical site preparation increased above-ground growth. Growth increment from mechanical site preparation was comparable to that from fertilization. Survival was not affected by any treatment. Fertilization enhanced root growth, more so in the shallow soil layers. Subsoil bulk density greatly restricted root growth, resulting in decreased above-ground growth. Chemical vegetation control made more soil water available to the seedlings during drought, resulting in increased seedling water potential. The effect of chemical vegetation control on seedling water potential was absent in the early growing season when soil moisture was abundant. Seedlings on plots treated with bedding-plus-fertilizer or bedding alone experienced stomatal closure at times of severe water stress while those treated with chemical vegetation control were able to continue net carbon dioxide assimilation. Fertilization did not increase needle nutrient concentrations, but increased needle weight, thereby increasing total nutrient content. Fertilization increased base cation concentrations in the soil solution, but had no effect on nitrogen and phosphorus concentrations. Intensive forest management was found to be a viable tool for optimum loblolly pine seedling growth and survival on poorly drained sites in the Western Gulf region of the United States.

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INTRODUCTION

A substantial area of seasonally wet, poorly drained sites is found within the Western Gulf region of the southern United States. These sites cover between 3.6% of the land area in Oklahoma and 16.4% in both Arkansas and Mississippi, and comprise over 3.75 million hectares in the states of Mississippi, Louisiana, Arkansas, Texas and Oklahoma (Hudnall and Williams 1989). Many of these sites experience standing water through much of the winter due to an underlying restrictive layer, most often a fragipan, resulting in an anaerobic atmosphere for roots and subsequent poor survival of planted tree seedlings. This condition may also result in leaching losses of nutrients to the subsoil fragipan. In addition, the sites experience frequent summer drought, which also may contribute to reduced tree growth. A major portion of these lands is used to grow loblolly pine (*Pinus taeda* L.) by timber manufacturing companies. These companies are interested in determining the most suitable cultural practices to obtain optimum loblolly pine growth and survival. Several such investigations have been conducted on the southeastern flatwoods in Florida. But there is a paucity of data relating to the Western Gulf flatwoods, particularly pertaining to nutrient status, ecophysiology of trees growing there, and above- and below-ground tree growth. The alternate wetting and drying of these flatwoods make it unclear as to whether moisture or nutrients or both play the key role in limiting growth and survival. Research has shown that the effects of mechanical and chemical site preparation can be very site specific, especially on poorly drained sites. This study was designed to test the relative importance of nutrition and water to loblolly pine seedling physiology and subsequent growth and survival in the Western Gulf flatwoods. Specifically measured were loblolly pine height and groundline diameter growth, survival, fine root growth, seedling water status and gas exchange during summer, soil nutrient leaching loss, and needle nutrients during the dormant season.

This manuscript follows the style of the journal Forest Science.

Objectives

The objectives of this research were to:

- Investigate the effect and nature of seasonal flooding on loblolly pine growth and survival in the Western Gulf flatwoods
- Determine the relative influence of moisture and nutrients on loblolly pine seedling growth and survival in the Western Gulf flatwoods
- Suggest the most suitable cultural practices for obtaining optimum pine growth and survival in these flatwoods

Hypotheses

- Mechanical site preparation will improve seedling growth and survival
- Chemical vegetation control will improve seedling water relations by means of increased soil water availability and therefore increase growth and survival
- Fertilization will increase growth by increasing available nutrients to seedlings
- Fertilization will enhance soil nutrient leaching loss
- Fertilization will enhance root growth
- Fertilization alone will increase undergrowth competition, resulting in less soil water availability at time of seedling water stress and subsequent lower seedling water potential
- Fertilizer and herbicide application will have an additive effect on growth

LITERATURE REVIEW

Loblolly pine has been identified as the most commercially important timber species in the southeastern United States, particularly in the mid-south (Schultz 1997). In 1989, loblolly pine growing stock totaled about 1.4 billion m^3, of which 43% grew in the Western Gulf states (Mississippi, Louisiana, Arkansas, Texas and Oklahoma). In addition to commonly recognized growth limitations to loblolly pine, such as nutrients and water deficits, on much of the lower coastal plains, excess soil moisture can also limit tree growth (Schultz 1997).

Site drainage is important in forest regeneration and poor drainage can adversely affect seedling growth and survival (Ralston 1965, Burton 1971). Excess soil moisture can lead to anaerobic conditions that inhibit root respiration and thus tree growth, and the soil might no longer be considered a utilizable resource for timber production (Riedl and Zachar 1984). In a study conducted by Moltchanov (1960), growing stock of a pine stand was directly correlated to depth of water table and water contained in a 1.0-m thick soil profile. The difference was as large as 50 m^3 ha^{-1} for a 0.3-m water table depth to 153 m^3 ha^{-1} for 5.5-m depth to water table. He also found that increasing water content after a certain level resulted in decreased growing stock.

Several concomitant mechanisms in a waterlogged soil result in inhibited forest growth. Whatever the mechanism, it usually begins with an anaerobic rhizosphere and restricted root respiration. The roots of forest trees are highly susceptible to oxygen deficiency and a continuous lack of soil oxygen can result in browning or blackening of normally pale root tips (Riedl and Zachar 1984). In a study conducted by Levan and Rhia (1986), significant root tip dieback occurred after three days of flooding in four pine species studied. In addition, turgor pressure of root tips can be greatly reduced where the oxygen requirement is highest. Fine roots are more susceptible to anaerobic respiration, but roots larger than 2-5 mm in diameter are less prone to permanent damage from oxygen deficiency (Riedl and Zachar 1984). Even though tap root lengths for loblolly pine (*Pinus taeda* L.) grown in drained and seasonally flooded treatments were similar, the number of lateral roots in the 0 to 6-cm soil horizon tended to increase with flooding (DeBell et al. 1984). Minirhizotrons, when used with a video camera, allow continuous and non-destructive observation of fine roots (Upchurch and Ritchie 1983, Vamerali et al. 1999).

Mechanical site preparation methods have been identified as major tools to overcome drainage problems. In addition, such methods have been identified to reduce competition, clear debris to facilitate planting, and reduce future fire hazard (Lowery and Gjerstad 1991). Disking, bedding, and ripping or subsoiling have been used most often where subsurface drainage is a major concern. Shearing followed by bedding on poorly drained sites can increase early seedling growth and survival by increasing aeration and removing woody competition (Dewitt and Terry 1983, Swindel et al. 1986). Bedding also promoted growth of slash pine (*Pinus elliottii* Engelm.) plantations on Spodosol flatwoods in Florida (Shiver and Rheney 1990). However, early-season growth and survival benefits from bedding may be more limited by late-season moisture deficits than non-bedded sites with comparable levels of interspecific competition (Lowery and Gjerstad 1991). Also early loblolly pine survival was comparable between mechanically prepared and check plots by other investigators (Wilhite and McKee 1985, Wittwer and Dougherty 1986). Ripping, fracturing the subsurface restrictive layer, not only promotes vertical drainage and reduces waterlogging, but also favors deep rooting. This aspect may become very important during summer droughts. Morris and Lowery (1988) identified ripping to be more effective in promoting deep rooting than any other tillage operation. Bedding, of all mechanical site preparation methods, can provide the greatest stimulation to N (nitrogen) mineralization by means of concentrating organic materials and surface soil into localized areas and creating a surface that is more rapidly warmed (Morris and Lowery 1988). Morris (1981) found that total inorganic-N concentrations in solution beneath beds on a flatwood Spodosols averaged 3.60 ppm compared to 2.31 ppm in interbed areas.

Chemical vegetation control combined with mechanical site preparation can stimulate significant increases in pine growth and survival. In a study by Wittwer and Dougherty (1986) in southeastern Oklahoma, total height of loblolly pine after two growing seasons was increased by approximately 10% by ripping, 23% by herbicide application and 49% by the combination of ripping and herbicide application when compared to the check plot. Stem groundline diameter (GLD) increased by 20%, 55% and 83% for these treatments, respectively. Similar results were observed by Shiver and Rheney (1990) for slash pine where they found that complete vegetation control provided the most consistent dramatic effect on growth in the flatwoods. Height, diameter, and survival were reduced by 33, 50, and 16%, respectively for loblolly pine seedlings growing with crabgrass (*Digitaria* spp.) compared to a monoculture (Ludovici and Morris 1997). Britt et al. (1991) reported that for a given biomass, loblolly pine trees in a low weed abundance treatment had higher mean relative growth rate and mean leaf area ratio throughout a six-year study period.

Flatwood soils are poor in nutrients. Fertilization at time of planting can enhance loblolly pine growth (Wilhite and McKee 1985, Swindel et al. 1988, Colbert et al. 1990, Haywood and Tiarks 1990, Albaugh et al. 1998). Continuous annual fertilization on poorly drained Spodosols increased loblolly pine growth over the first four years (Neary et al. 1990). On a somewhat poorly drained site in the lower Atlantic Coastal Plains in South Carolina, trees fertilized with phosphorus (P) were significantly taller by 0.3 m after five years (Wilhite and McKee 1985). Alternating aerobic and anaerobic conditions in a waterlogged soil encourages N loss through sequential ammonification – nitrification – denitrification reactions (Reddy and Patrick 1976) and can cause up to a 25% decrease in total N (Reddy and Patrick 1975). The effect of chemical weed control and fertilization can be additive (Neary et al. 1990, Swindel et al. 1988). However, Haywood and Tiarks (1990) reported that fertilization in combination with weed control did not significantly increase volume growth because of increased mortality associated with an increase in observed herbaceous plant yields.

Foliar nutrient concentrations above minimum levels are important in maintaining needle physiology (Allen 1987). Needle N concentration is associated with photosynthetic pigments and proteins and affects photosynthetic acclimation to light intensity (Field and Mooney 1986, Evans 1989). In C_3 plants, approximately 75% of leaf N is committed to the biochemical and physiological processes of photosynthesis (Field and Mooney 1986). However, significant leaf N increase by fertilization did not affect photosynthetic rate in a four-year-old loblolly pine trial in southeastern Oklahoma (Zhang et al. 1997). Alternatively, fertilization with P resulted in significant increases in net photosynthetic rate and dry matter of loblolly pine seedlings and a strong relationship was found between needle P concentration and rate of net photosynthesis (Rousseau and Reid 1990). Murthy et al. (1996) reported an increased level of foliar N in loblolly pine seedlings fertilized and grown in ambient CO_2 concentration, resulting in a 24% increase in light-saturated net photosynthesis. However, irrigation, and not fertilization, increased mid-day light-saturated net photosynthesis in loblolly pine after two years of intensive cultural treatments (Samuelson 1998).

Water stress is considered to be one of the most important environmental factors affecting survival, growth and distribution of plant species (Kramer 1983). Water stress in plants can largely decrease leaf photosynthesis (Seiler and Johnson 1985) which is a result of both increasing resistance to CO_2 diffusion and a reduction in the efficiency of the photosynthetic mechanism (Boyer 1976, Hinckley et al. 1981). Chemical site preparation has been shown to increase soil moisture availability resulting in higher water potential in loblolly pine seedlings (Greet et al. 1991).

Nutrient leaching in waterlogged soils is a common phenomenon. Understanding soil chemistry is important to foresters (Marques et al. 1996) for silviculture of a forest has been associated with soil chemistry (Ranger and Nys 1994, Matzner et al. 1983, and Bormann and Likens 1979). Several mechanisms of collecting soil solutions have been identified, of which zero tension lysimeter and suction-cup lysimeters are most common (Marques et al. 1996). Despite their reported inconsistencies for different nutrients (Zabowski 1989, Ranger et al. 1993, and Zabowski and Ugolini 1990), suction cup lysimeters have been identified as a simple method for *in situ* soil sample collection (Wu et al. 1995) and have been widely accepted (Macduff et al. 1990, Lord 1992, Webster et al. 1993).

METHODS AND MATERIALS

Site selection

Ten sites were selected in the southern coastal plain of Arkansas (between $32^{0}47'$ and $33^{0}38'$ N, and $91^{0}42'$ and $92^{0}38'$ W) on lands of three different collaborating companies (International Paper, The Plum Creek Timber Company, and Potlatch Corporation). Criteria used for site selection were uniformity in topography and soil properties, depth to fragipan and soil drainage. These sites are located within a 30-km radius. All sites are located on upland terraces with a fine-silty textured soil, either Ultisols or Alfisols with an argillic endopedon. Surface soils were a silt loam texture while subsurface soils were silty clay loam, except for one site which had a clayey subsurface. Depth to fragipan varied between 25 and 65 cm (Appendix 1). Average annual precipitation for the region is 140 cm, with seasonal extremes during wet winters and dry autumns. Daily temperatures average 22 ^{0}C during the growing season (March – September) and 11 ^{0}C during the dormant season (October – February) (Cain and Shelton 2001). Four sites were planted in January 1998 and six additional sites were planted in early 1999. All sites are listed in Appendix.

Experimental design and treatments

All sites were established in a completely randomized design, treatments being fertilization, chemical vegetation control and mechanical site preparation. Sites established in 1998 were all bedded with four plots on each site receiving one of the following treatments assigned randomly:

- Control (BED-N): no fertilization or chemical vegetation control
- Continuous fertilization (BED-F)
- Complete vegetation control (BED-CV)
- Complete vegetation control and continuous fertilization (BED-CVF)

All sites established in 1999 have six plots in each receiving one of the following treatments assigned randomly:

- Bedding control (BED-N)
- Bedding plus continuous fertilization (BED- F)
- Bedding plus complete vegetation control (BED- CV)
- Bedding plus complete vegetation control and continuous fertilization (BED-CVF)
- Flatplanting control (FP-N)
- Flatplanting plus chemical vegetation control and fertilization at year of planting (FP-VF)

Plot layout

Each whole plot contained 13 rows with 18 seedlings on each row, or 234 trees. Spacing varied from 3.3 m to 4.0 m between beds and 1.8 to 2.4 m between seedlings for a planting density of 1040 to 1680 seedlings per hectare. However, spacings among plots within each site were uniform. Variations in spacing between sites occurred primarily due to different site preparation teams or companies, equipment used, on-site slash, and drainage. The central seven rows by ten seedlings were used for measurement plots, allowing a three-row buffer on each side and a four-seedling buffer on each end of the plot. Treatments were applied throughout the whole plots. A whole plot covered an area of approximately 0.4 ha, whereas the measurement plot accounted for half of that.

All plots within any site were established along or across the bed depending on site uniformity and drainage. Any disturbance, such as pimple mounds, pits, etc. were excluded, unless land was limiting. All plot boundaries were well marked with PVC pipes. Each measurement seedling was flagged and a metal wire was placed at the beginning of each measurement row.

Seedling establishment

All sites were planted with loblolly pine. Seedlings were container grown in nurseries owned by the corresponding companies. Genetic families were chosen based upon site characteristics. Following establishment in the nursery, seedlings were hand-planted by the respective companies on their own sites. The flatplanting plots were chemically sprayed and burned while the bedded plots were mechanically site prepared for plantation.

Mechanical site preparation

All sites were bedded and subsoiled using a combination plow. A combination plow, sometimes called a three-in-one plow, contains:

- A vertical coulter to cut down through stumps and debris
- A subsoiling shank to rip and shatter compacted subsoil layers
- Multiple disks to form an elevated bed.

The use of a combination plow requires shearing of harvest residues, which is done by using a V-blade. All sites were prepared using one-pass of the combination plow, except two sites in Crossett, Arkansas which required an additional pass to achieve a desired bed height. Despite an attempt to control and minimize harvest residues among sites, they varied (as visually observed).

Fertilization

All fertilized plots received 250 kg / ha DAP (diammonium phosphate), 125 kg / ha KCl (muriate of potash) and a 100 kg / ha mix of micronutrients (Mn – 0.04%; Ca – 4.0%; Mg – 2.5%; S – 2.2%; B – 0.47%; Cu – 0.14%). Fertilizers were broadcast by hand throughout the whole plot in early spring, well before the growing season started.

Chemical vegetation control

All plots to be treated with herbaceous weed control were sprayed with glyphosate and sulfometuron in 1999 and imazapyr and sulfometuron in 2000. Herbicides were applied with backpack sprayers at recommended rates. To ensure complete vegetation control (85% bare-ground), plots were resprayed as necessary.

Data collection

Soil physical and chemical properties

Soil samples were collected from each site from one location for all layers up to 1m depth. These samples were used for determining soil textural class by the dispersion method. In addition, bulk densities of the surface layer and the restrictive subsoil layer of each site were determined. A soil density sampler was used to collect undisturbed soil cores of known volume (100 cm^3). The sample core was then placed in a sealed plastic bag and stored in a cool box until carried to the laboratory. The cores from all sites were oven dried at 70 ^{0}C until no further weight change was detected. After drying, cores were immediately weighed. The bulk density of the soil sample was determined as:

$$\text{mass of oven dry soil (gm) / volume of oven dry soil (100 cm}^3\text{)}$$

Surface layer soil samples were used for determining organic matter content while both surface and subsurface layer samples were used to determine the P, K, Ca and Mg content (Table 1).

Height and groundline diameter (GLD)

Height and groundline diameter were collected at the end of each growing season to determine annual growth. Height was measured using a height pole to the nearest 0.5 cm. Groundline diameter was measured using a slide caliper to 1.0 mm. Seedling survival was determined when growth data were collected.

Table 1. Chemical properties of surface (Ah) and sub-surface (Bx) layers of 10 sites established in 1998 and 1999 in southern Arkansas. Data are given in the format mean ± one standard deviation.

		pH (H_2O)	Organic Matter (%)	P (ppm)	K	Ca	Mg	CEC	Base Saturation (%)
					(meq / 100 gm soil)				
1998-Sites	Surface	4.7 ± 0.1	1.6 ± 0.1	1.4 ± 1.3	0.19 ± 0.05	1.74 ± 0.32	0.57 ± 0.23	11.5 ± 1.8	22.1 ± 2.7
	Sub-surface	4.4 ± 0.1	-	0.5 ± 0.2	0.05 ± 0.02	0.26 ± 0.18	0.29 ± 0.27	6.1 ± 2.5	11.2 ± 4.9
1999-Sites	Surface	4.5 ± 0.2	1.8 ± 0.1	1.5 ± 0.4	0.13 ± 0.02	1.44 ± 0.34	0.55 ± 0.23	12.4 ± 2.6	17.5 ± 5.7
	Sub-surface	4.9 ± 0.2	-	0.2 ± 0.0	0.05 ± 0.01	0.33 ± 0.02	0.51 ± 0.37	11.1 ± 3.3	17.0 ± 16.2

Foliar nutrient concentration

Needle samples from each plot were collected in January each year. Approximately 50 fascicles, no more than five from any tree, were collected from each plot. Needle samples were then oven dried and ground followed by a wet digestion (Li_2SO_4, H_2SO_4, and H_2O_2). Nitrogen and P concentrations were determined by using a Alpkem FS3000 (College Station, TX, USA) and base nutrients (K, Ca and Mg) were determined by atomic absorption spectrophotmetry (Varian (Mulgrave, VIC, Australia) SpectrAA 220-FS). These data were used to recommend fertilizer application in the following year. Needle nutrient concentrations recommended by the North Carolina State Forest Nutrition Coop (NCSFNC) were used as a guideline for desired concentration.

Soil nutrient leaching loss

Three suction-cup lysimeters were installed in each plot to the depth of the fragipan. Holes equal to the diameter of the lysimeter tubes were augered on three consecutive inter-bed aisles near the center of the measurement plot until the auger hit the fragipan which could be felt by increased resistance to auger penetration and friction between the fragipan and the auger. The tubes were installed at time of extremely wet soil conditions and standing water along with silt-mud immediately filled the narrow gaps between the lysimeter tube and auger-cut soil surface. Once the tubes were settled in the soil, soil solution samples, obtained at -0.05 MPa suction pressure, were collected a few weeks after fertilization and at several dates each year to determine leached nutrients (Total N, total P, K, Ca, and Mg) from the rooting zone above the fragipan. Pressures were applied by using a manual pump showing applied pressure on a gauge and left under pressure for a 24-hr period after which a maximum of 150 ml of solution was collected when available.

Minirhizotron root observation tubes

Three minirhizotron root observation tubes were installed in each bedding control (BED-N) and bedding plus fertilization (BED-F) of the 1998-sites at a 45^0 angle beneath seedlings. These are clear plastic tubes around which roots grow allowing repeated non-invasive root measurements (Pritchard et al. 2001). Root pictures were taken at 37 index locations, 13.5 mm apart, within each tube allowing root exploration to a vertical depth of 37 cm. The camera was equipped with an indexed handle which allowed repeated measurements at precise locations over time (Johnson and Meyer 1998). These observations were repeated five times between late summer of 1998 and late spring of 2000. A BTC 2 minirhizotron video microscope was used to capture images on a portable computer using I-CAP image capture system software (Bartz Technology Corporation, Santa Barbara, CA http://www.bartztechnology.com). A total of 4,440 (24 tubes * 37 depth * 5 sessions) images were captured for analysis. Following acquisition of the images of all sessions, they were digitally traced to determine the number, and total root length and diameter of live and dead roots – which then allowed calculation of parameters such as root turnover and root length density (Tingey et al. 2000).

To facilitate representation and understanding, root measurement attributes have been grouped and averaged for the following depths:

Depth1	0 – 7 cm	(index location 1-7)
Depth2	7 – 14 cm	(index location 8-14)
Depth3	14 – 20 cm	(index location 15-20)
Depth4	20 – 26 cm	(index location 21-26)
Depth5	26 – 32 cm	(index location 27-32)
Depth6	32 – 37 cm	(index location 33-37)

Water relations and gas exchange data

Water potential data, from four different times daily (0900, 1200, 1500 and 1800 hours) during the 1999 and 2000 growing seasons, were collected using a pressure bomb apparatus according to the procedures described by Scholander et al. (1965). Three samples per plot per hour were collected and needles from the same seedlings were used for all measurement hours. Due to time constraints only one site (PC3) was chosen for water relations and gas exchange data collection. Stomatal conductance, transpiration, net photosynthesis and intercellular CO_2 concentration were determined for seedlings from all treatments at four different measurement hours using a Li-COR 6200 (Lincoln, NE). The collection of these data was concomitant to collection of water potential data and used the same seedlings sampled for water potential.

Volumetric soil moisture content

Volumetric soil moisture content to 15 cm was determined using time domain reflectometry (Trase system manufactured by Soilmoisture Equipment Corp., Santa Barbara, CA) for all water relations and gas exchange measurement hours.

Data Analysis

All data were analyzed using SAS software package (Version 6.12, SAS Institute Inc., Cary, NC). All statistical significance was calculated at $\alpha = 0.05$ unless otherwise mentioned. Linear contrasts were used to compare treatments in the following groups:

Group	Treatments
FERT	BED-F, BED-CVF and FP-VF
Non-FERT	BED-N, BED-CV and FP-N
HERB	BED-CV, BED-CVF and FP-VF
Non-HERB	BED-N, BED-F and FP-N
BED	BED-N, BED-CV, BED-F, and BED-CVF
FLAT	FP-N and FP-VF

The following weights were used to test the effect of fertilization, herbicides and mechanical site preparation (treatment order: BED-CV, BED-CVF, BED-F, BED-N, FP-N, FP-VF):

	Contrast	Weight
Fertilization effect	FERT vs. non-FERT	-1, 1, 1, -1, -1, 1
Herbicide effect	HERB vs. non-HERB	1, 1, -1, -1, -1, 1
Mechanical site preparation effect	BED vs. FLAT	1, 1, 1, 1, -2, -2

Duncan's New Multiple Range Test (NMRT) was used at $\alpha = 0.05$ to separate means where necessary.

RESULTS AND DISCUSSION: ABOVE- AND BELOW-GROUND GROWTH

Height and groundline diameter

Fertilization significantly increased height and groundline diameter after all growing seasons on all sites. After three years on the 1998-sites, BED-F seedlings grew 5% and 11% more than BED-N seedlings in height and GLD, respectively. Height and GLD growth for the FERT treatments (FP-VF, BED-F, and BED-CVF) on the 1999-sites after two years were 16% and 24% greater than the non-FERT treatments (FP-N, BED-N and BED-CV).

Chemical vegetation control did not affect height growth in the first growing season of either site establishment year (1998 and 1999). However on the 1999-sites, chemical vegetation control significantly increased height growth in the second growing season. The effect of chemical vegetation control on the 1998-sites during subsequent years is not reported due to herbicide spray damage on seedlings in these plots. Groundline diameter was not affected by chemical vegetation control on the 1998-sites during their first growing season, but was significantly higher for HERB treatments on the 1999-sites after all growing seasons (Table 2).

Mechanical site preparation significantly increased height and GLD growth. After the first growing season, height and GLD growth was 15% and 12% more, respectively, for BED-N than FP-N. These values were 27% and 18% (for height and GLD, respectively) after two growing seasons.

The effect of each treatment was additive to the other. Volume index (Height X GLD X GLD) gains from BED-N to BED-CV and BED-N to BED-F at the end of first two growing seasons measured were 12% and 66%, respectively, whereas this value for BED-N to BED-CVF was 86% (Figure 1). Maximum volume gain was observed from the least intensively managed plot (FP-N) to the most intensively managed plot (BED-CVF) at the end of each growing season at 110%

Table 2. Height and groundline diameter of loblolly pine seedlings planted in 1998 and 1999 on bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Data followed by same letter within column in same plantation year are not significantly different.

	Jan-1999		Feb-2000		Jan-2001	
	Height (cm)	GLD (mm)	Height (cm)	GLD (mm)	Height (cm)	GLD (mm)
1998-Sites						
BED-N	43 b	13 b	134 b	23 b	240 b	35 b
BED-CV	44 b	12 b	-	-	-	-
BED-CVF	50 a	15 a	-	-	-	-
BED-F	49 a	14 a	142 a	26 a	251 a	39 a
1999-Sites						
FP-N	-	-	41 d	8 d	98 e	17 e
FP-VF	-	-	41 d	10 b	115 d	22 c
BED-N	-	-	47 c	9 c	124 c	20 d
BED-CV	-	-	48 c	10 b	130 b	21 c
BED-F	-	-	54 a	10 b	149 a	24 b
BED-CVF	-	-	51 b	11 a	143 a	26 a

for 1998 and 190% for 1999. Volume index gain from mechanical site preparation (FP-N → BED-N) was similar to that of fertilization on the mechanically prepared site (BED-N → BED-F) at the end of the first growing season and more in the second growing season (Figure 1), suggesting that mechanical site preparation can be as beneficial as fertilization in the early years of seedling establishment on these and similar sites.

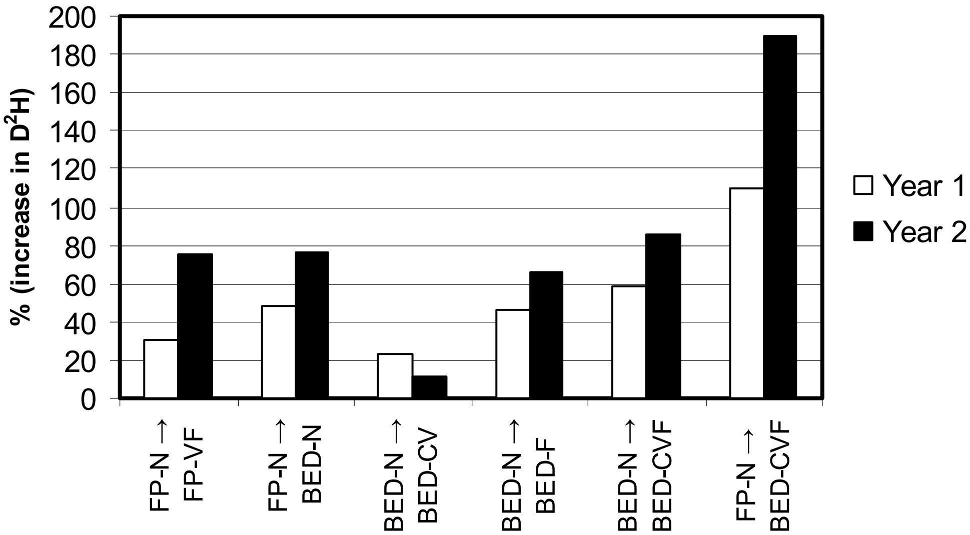

Figure 1. Volume index (D^2H) gain of loblolly pine seedling from combination of different cultural practices after two growing seasons on six sites planted in early 1999 in southern Arkansas. An arrow in X-axis label indicates percentage gain from the treatment following the arrow compared to the treatment preceding it. Treatments were bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF).

There was a significant site effect among the 1998-sites. This was due to lower growth observed on one of the sites (IP1) at the end of all growing seasons (Figure 2). This may be attributed to shallow depth to the fragipan and high bulk density on this site. Bulk densities higher than 1.45 gm/cm^3 can limit tree growth on silty clay loam soils (Morris and Lowery 1988), where subsoil bulk density for IP1 site was found at 1.72 gm/cm^3. Gent et al. (1983) also showed that higher (>1.4 gm/cm^3) bulk densities can restrict loblolly pine growth.

The growth trends on 1998- and 1999-sites were similar across the sites. After their first growing season, 1998-sites grew 46.5 cm in height and 13.5 mm in GLD, averaged across all study sites established that year, whereas 1999-sites grew 47.0 cm and 10.0 mm in height and GLD, respectively. These values, after two growing seasons, were 138.0 cm and 24.5 mm for 1998-sites and 126.5 cm

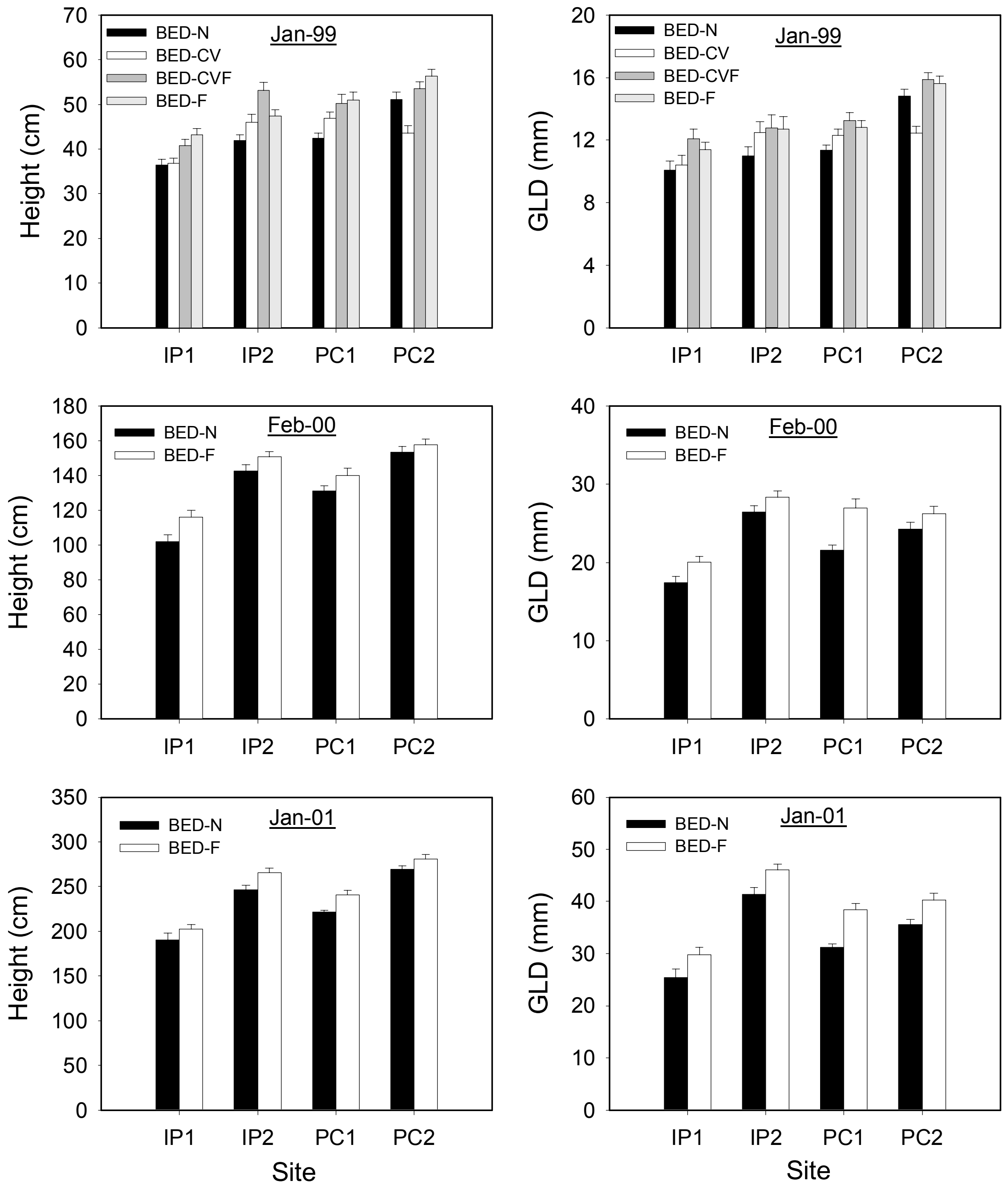

Figure 2. Loblolly pine height and groundline diameter (GLD) growth on four sites established in 1998 in southern Arkansas using bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), and bedding plus continuous complete vegetation control and fertilization (BED-CVF). Vertical bars indicate one standard error.

and 22.0 mm for 1999-sites for height and GLD, respectively. Although these values may largely be attributed to initial seedling size at time of planting, which was measured only for two 1998-sites and found to vary non-significantly, they can also be associated with similar precipitation totals and their temporal distributions in those two years (113.1 and 117.2 cm in 1998 and 1999, respectively – data collected from National Climatic Data Center website at http://www.ncdc.noaa.gov).

Although growth trends were similar for the two site establishment years (1998 and 1999), response to fertilizer varied between years. Despite the fact that fertilization was found significant for all years on all sites established in both 1998 and 1999, sites that were established in 1999 showed a greater response to fertilization. The fertilization effect on growth in the 1998-sites was expected to be higher than observed after three years. Although BED-F had significantly greater height than BED-N after three years, the effect was not visible except for more vigorous foliage on the BED-F seedlings.

Survival

Survival was not affected by mechanical site preparation, fertilization or chemical vegetation control. Survival on the 1998-sites averaged 82% after three years, and 70% after two years on the 1999-sites. Lowest survival was observed for BED-N in the 1998-sites and for FP-N in the 1999-sites during the January, 2001 measurement period. Survival declined steadily through the years for all sites, significantly for the 1999-sites and non-significantly for the 1998-sites (Figure 3). Seedlings of the 1998-sites showed the highest mortality during the 2000 growing season, their third year of growth. The 1999-sites averaged 23% mortality during the first year.

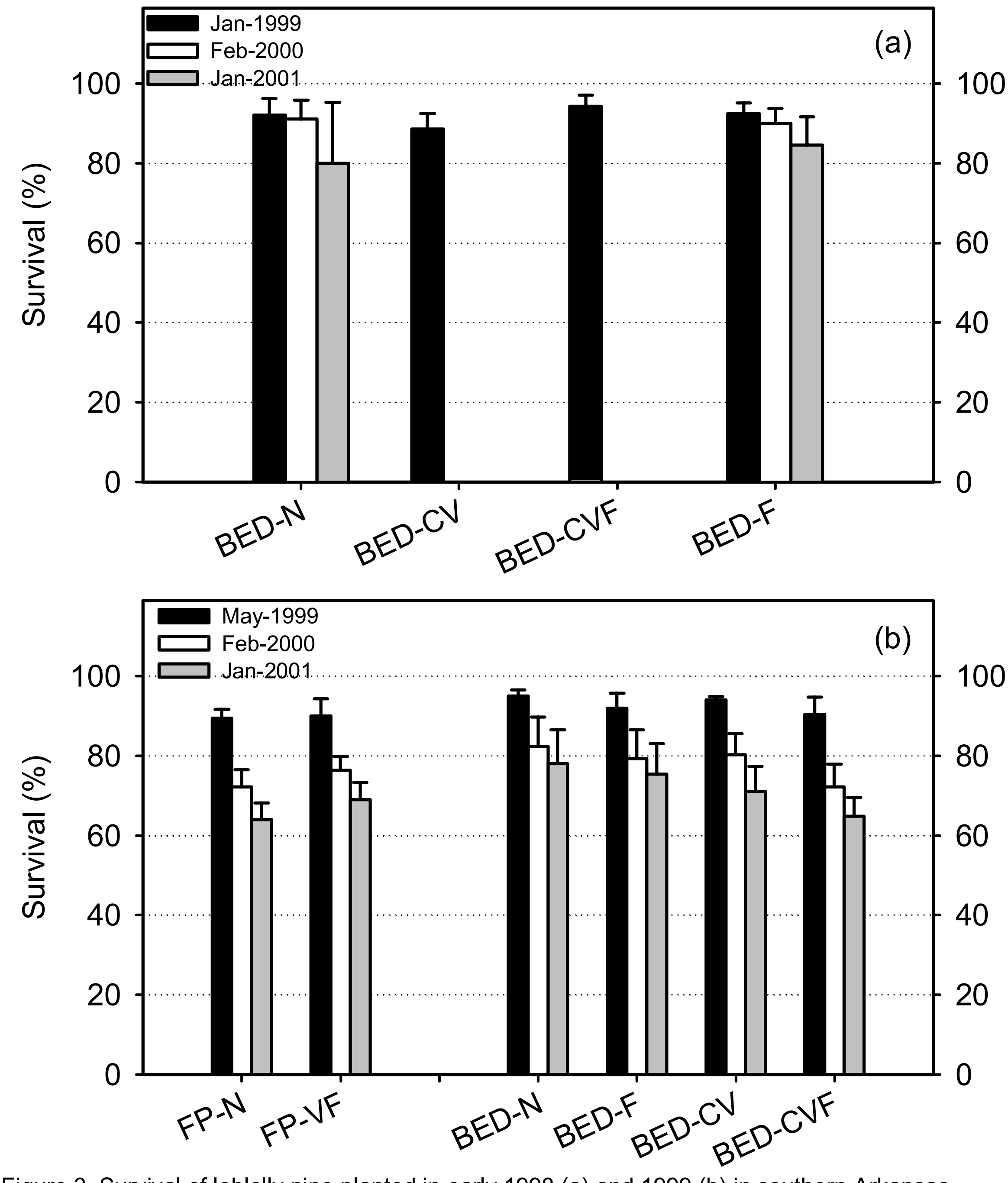

Figure 3. Survival of loblolly pine planted in early 1998 (a) and 1999 (b) in southern Arkansas using bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

Even though flatplanted plots had consistently lower survival than BED-N, they were not significantly ($P = 0.28$) different from the bedded plots. During the last measurement period in January 2001, BED-N seedlings exhibited 78% survival whereas seedlings of FP-N exhibited 64% survival. Seedling survival differences between these two plots (BED-N and FP-N) were as large as 40% for sites with very poor drainage. The survival gain from the bedding (FP-N → BED-N) was higher than that from the chemical vegetation control (BED-N → BED-CV). Although survival values were collected only at the end of the year, which limits the scope of comparing the effect of winter waterlogging and summer drought on survival, it can be interpolated from superior survival due to mechanical site preparation that winter waterlogging may play an important role in seedling survival on these sites.

Similar to its lower growth when compared to other 1998-sites, IP1 showed lower survival values as well. Figure 4-a shows survival values for three years for BED-N seedlings on four sites established in 1998. Site 'IP1' had the highest sub-surface bulk density (1.72 gm/cm^3) and the lowest survival. In addition survival on this site decreased by a considerable margin (77% in Feb-00 to 34% in Jan-01) through years when survival for other sites remained unchanged (Figure 4-a). Similarly on 1999-sites, the effect of mechanical site preparation on survival increased with lower subsurface bulk density compared to a higher bulk density which caused seedling mortality for all treatments (Figure 4-b). For example, on site 'IP3', 'PC3' and 'PL2', where bulk density is below 1.55 gm/cm^3, bedding showed a greater effect on survival. On sites with bulk densities higher than 1.55 gm/cm^3, such as 'PL1', 'PL3' and 'PL4' survival may have been limited due to vertical root growth. This is further supported by the observation that survival of BED-N and FP-N seedlings for these sites after the first year have been comparable as rooting depth for these seedlings at age one may not have yet been restricted by subsoil strength.

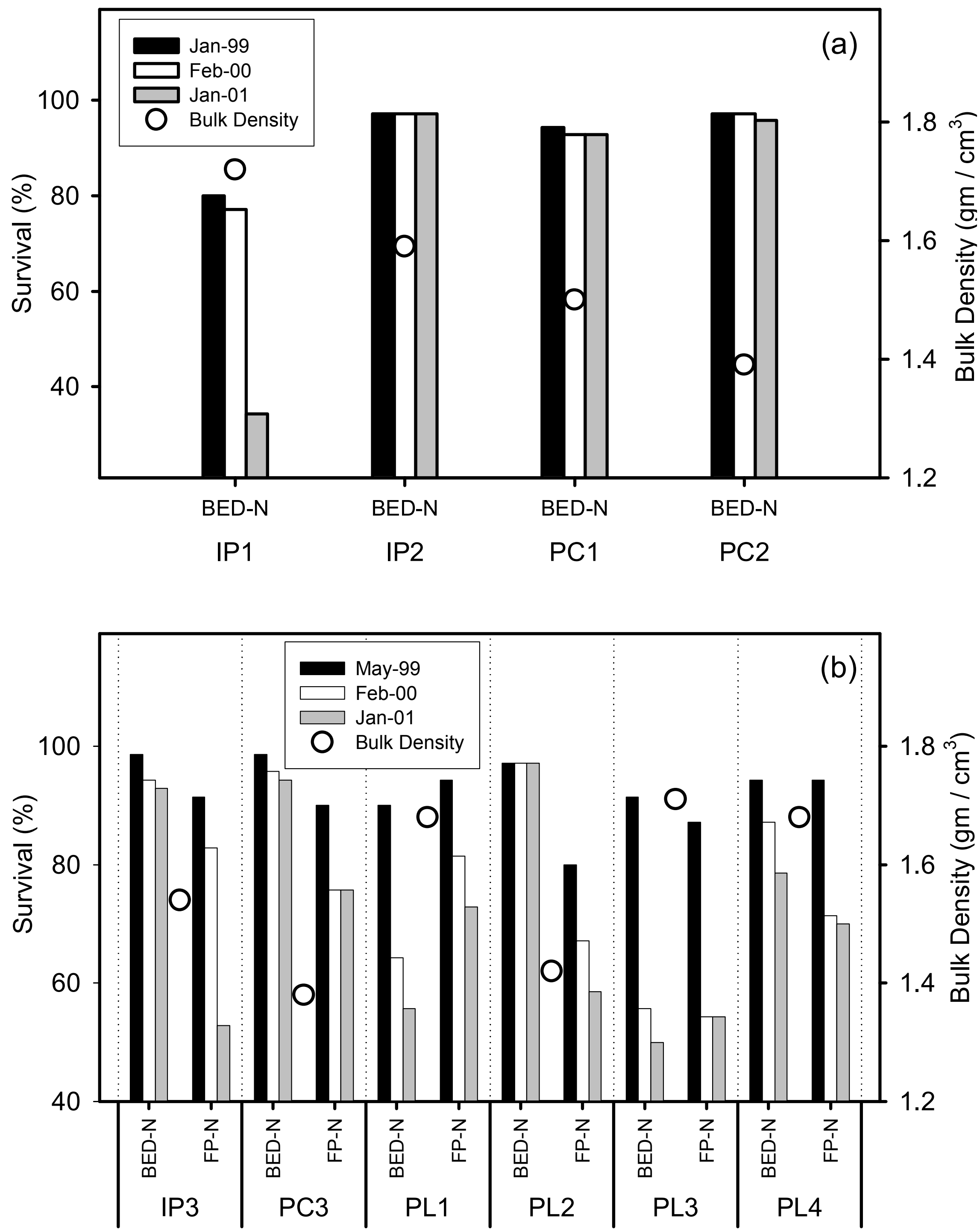

Figure 4. Survival of loblolly pine seedlings on ten different sites established in 1998 (a) and 1999 (b) in southern Arkansas using flatplanting (FP-N) and combination plow (BED-N), and subsurface bulk density of each site.

Root standing crop

Fertilization significantly affected total root length and diameter. More live roots per frame were observed with the minirhizotron for fertilized (BED-F) than for unfertilized (BED-N) seedlings. For all depths and sampling sessions, total root lengths per frame for fertilized and unfertilized seedlings were 7.79 and 6.43 mm, respectively. Total root diameter per frame was also higher for fertilized (0.54 mm) than for unfertilized (0.48 mm) seedlings (Table 3). There were more roots available at shallow depths than at the deeper depths, with the greatest number at Depth2 (7 – 14 cm). There were, in the upper two depths (0 – 14 cm), 56% of total root length and 53% of total root diameter across all depths (0 – 37 cm). A fertilization effect on root standing crop was not present in the deepest depth (32 - 37 cm) where fertilized seedlings had 23% and 10% lower total root length and diameter, respectively, than those of unfertilized seedlings. Maximum root stock was observed in May, and minimum in January (Figures 5 and 6).

Table 3: Standing root crop characteristics, root production and root mortality of loblolly pine seedlings planted on fertilized bedded plots (BED-F) and bedded control plots (BED-N) in four sites in southern Arkansas. Data followed by same letter within row are not significantly different at α = 0.05.

	BED-N	BED-F	Probability
Standing root crop characteristics			
Total root length (mm/frame)	6.43 b	7.79 a	0.001
Number of live roots (#/frame)	0.91 b	1.28 a	0.001
Total root diameter (mm/frame)	0.48 b	0.54 a	0.02
Production			
Root length production (mm) (Jan-99 to Mar-99)	0.36 a	0.29 a	0.39
Root length production (mm) (Mar-99 to May-99)	1.10 b	2.81 a	<0.0001
Root length production (mm/day) (Jan-99 to Mar-99)	0.006 a	0.005 a	0.39
Root length production (mm/day) (Mar-99 to May-99)	0.015 b	0.038 a	<0.0001
Mortality			
Number of dead roots (#/frame)	0.53 a	0.57 a	0.62
Root length mortality (mm) (Jan-99 to Mar-99)	0.41 a	0.23 a	0.14
Root length mortality (mm) (Mar-99 to May-99)	0.47 a	0.33 a	0.28
Root length mortality per day (mm) (Jan-99 to Mar-99)	0.007 a	0.004 a	0.14
Root length mortality per day (mm) (Mar-99 to May-99)	0.006 a	0.005 a	0.28
Root length turnover	0.34 a	0.28 a	0.06

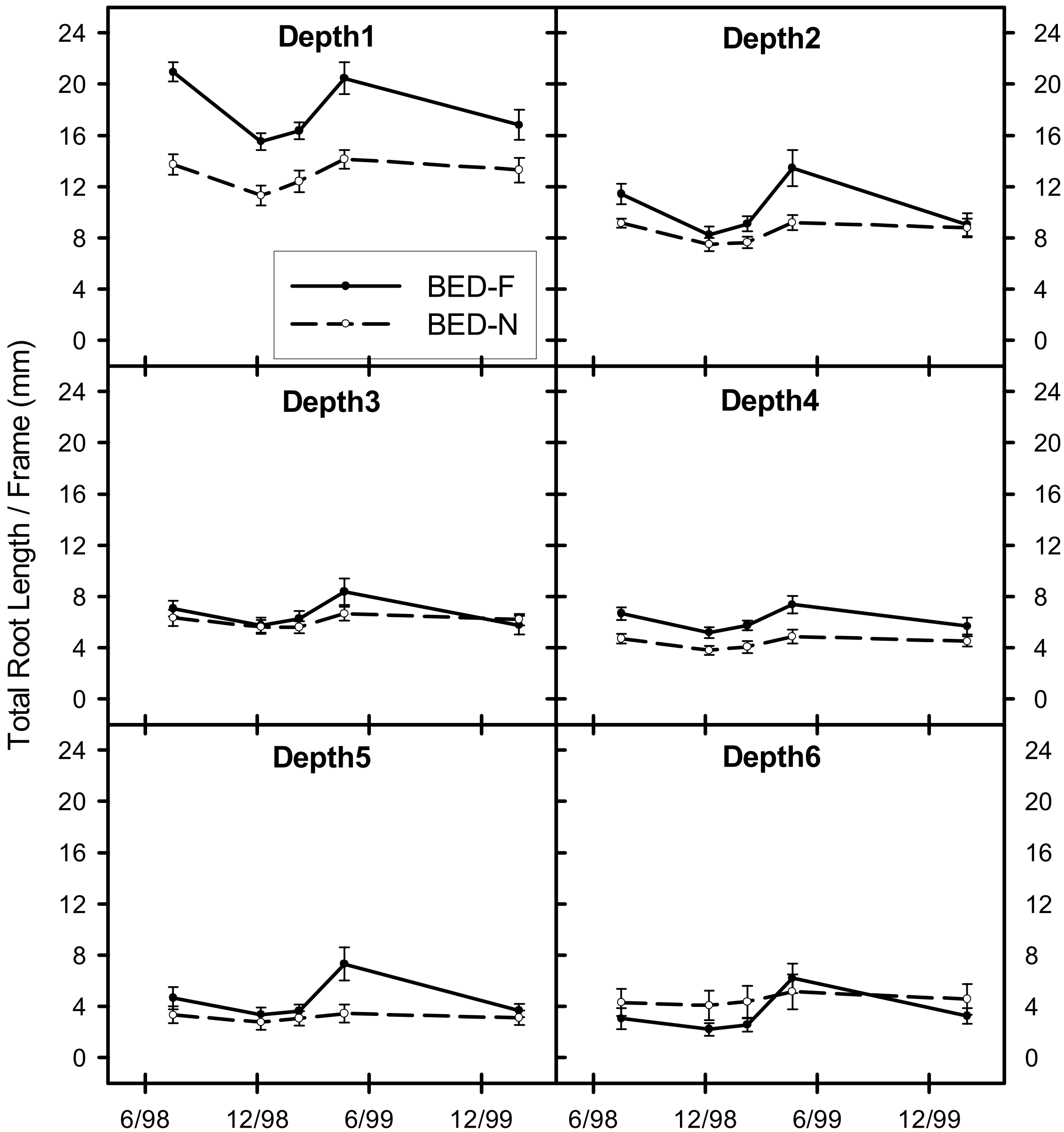

Figure 5. Total root length per frame for six depth classes, Depth1 (0 – 7 cm), Depth2 (7 – 14 cm), Depth3 (14 – 20 cm), Depth4 (20 – 26 cm), Depth5 (26 – 32 cm), and Depth6 (32 – 37 cm), of loblolly pine seedlings planted on fertilized bedded plot (BED-F) and non-fertilized bedded control plot (BED-N) in four sites in southern Arkansas.

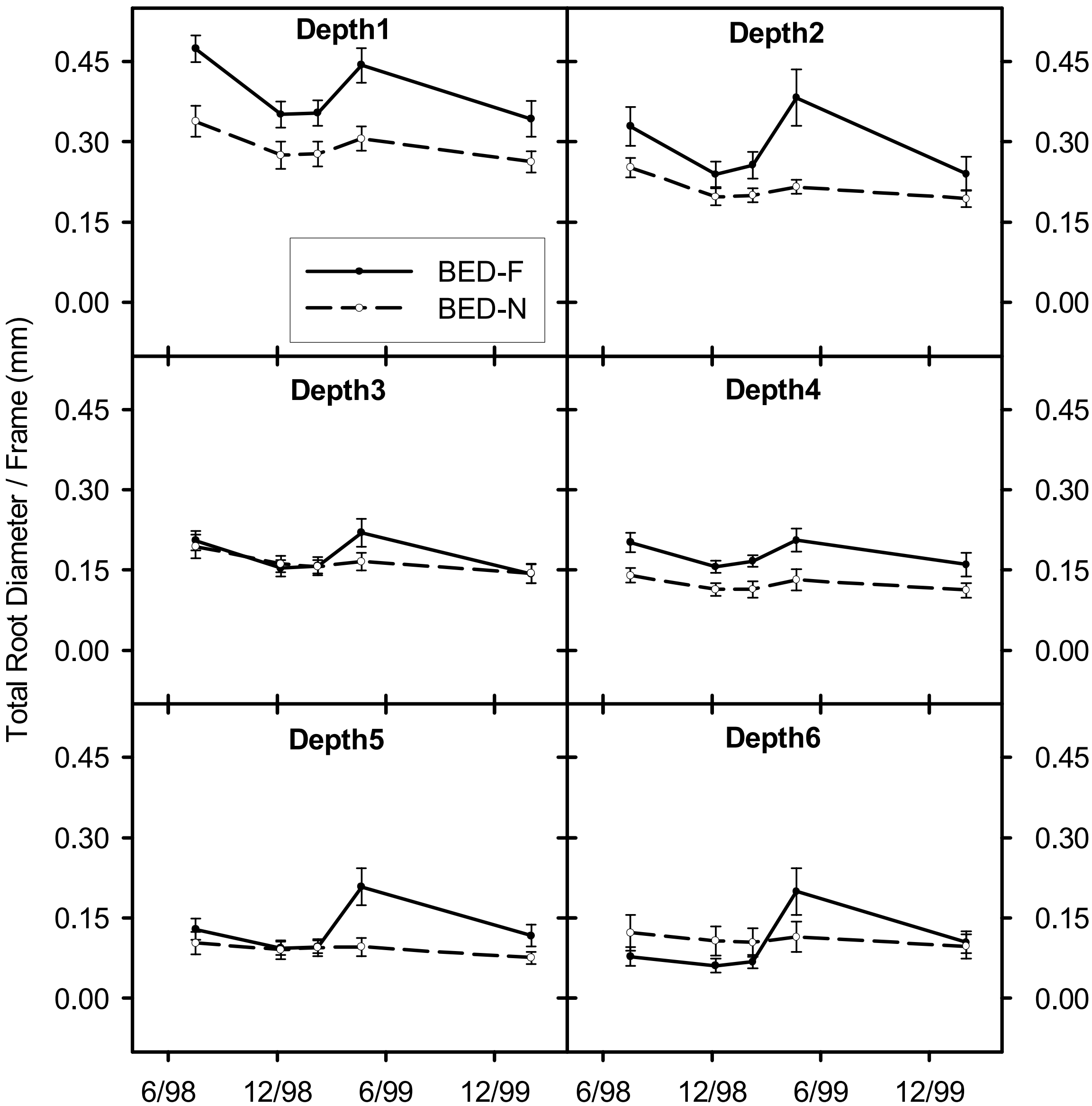

Figure 6. Total root diameter per frame for six depth classes, Depth1 (0 – 7 cm), Depth2 (7 – 14 cm), Depth3 (14 – 20 cm), Depth4 (20 – 26 cm), Depth5 (26 – 32 cm), and Depth6 (32 – 37 cm), of loblolly pine seedlings planted on fertilized bedded plot (BED-F) and non-fertilized bedded control plot (BED-N) in four sites in southern Arkansas.

Root production

Enhanced root production resulting from fertilization was observed immediately after fertilization between March and May measurements (Table 3). Root length production for fertilized seedlings was 155% greater than that for the unfertilized seedlings. Overall root production for both plots was also maximum between March and May measurements suggesting that there could be an additive effect of improved soil drainage condition and increased soil temperature to fertilizer application to root production. However, Sword et al. (1996) did not observe the effect of fertilization on root growth until July on a site in Rapides Parish, LA. New root production was comparable for all depths during these periods. Root production was minimal between January and March likely because of reduced rhizosphere from waterlogging and cooler temperatures compared to the succeeding months in summer (Table 3). New root length production decreased with depth between January and March measurements (Figure 7). However, between March and May measurements, new roots were produced in the deeper soils (Depth5 and Depth6 in Figure 7). Sword et al. (1996) observed that more new root lengths were added in the deeper soils in late summer than early summer. However, no measurement was taken beyond May for this study and it was not possible to document likely enhanced new root growth in the lower depths throughout summer.

Root mortality and turnover

Root length mortality for unfertilized seedlings was greater than for the fertilized seedlings, but not significantly (Table 3). Unlike root length production, mortality between January and March did not differ from that between March and May. Comparable mortality for fertilized and unfertilized seedlings, but enhanced production for fertilized seedlings compared to those of unfertilized-N led to higher standing root crop for this treatment in summer, except for total root length at Depth6 (Figures 5 and 6). Root mortality did not differ among depths. Root turnover index values were similar for treatments. Root turnover did not differ among depths, although was lowest for the upper two depths (Depth1 and Depth2) supporting findings by Sword et al. (1996) that more roots are produced and existing crops are replaced faster in the deeper soil.

Subsoil bulk density was observed to greatly influence root growth. Minimal root growth was observed in the deeper depths for 'IP1' compared to the other sites. This site had 3.7% of its total root length in the lowest two depths (26 – 37 cm) compared to 18.4%, 23.0% and 25.0% for 'IP2', 'PC1' and 'PC2', respectively (Figure 8). Subsoil bulk density for IP1 was 1.72gm/cm^3 which can greatly reduce root growth. This is also supported by the fact that IP1 had the lowest growth and poorest survival. Rooting depth and amount of fine roots in the deeper soil are crucial for seedling growth and survival when the water table is low. Restricted root growth in the deeper soil due to high soil strength may be the primary cause for poor growth and survival found in the 'IP1' site.

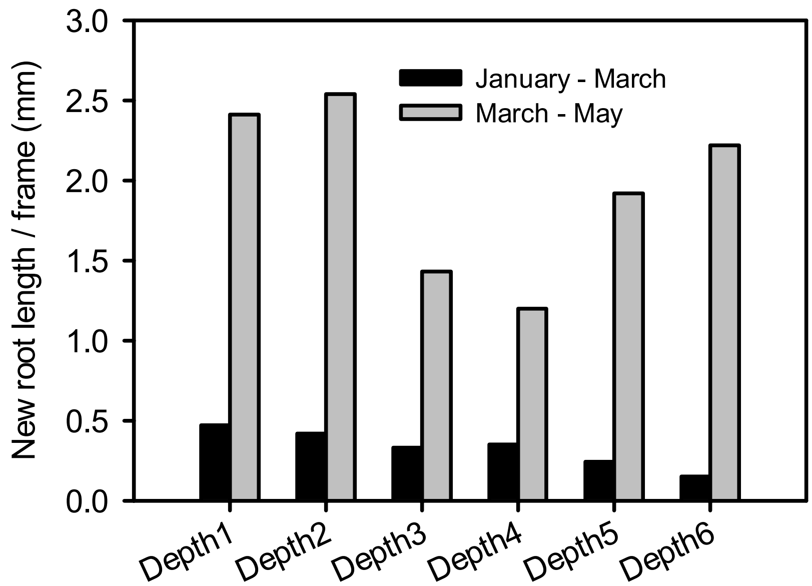

Figure 7. New root length per frame for six depth classes, Depth1 (0 – 7 cm), Depth2 (7 – 14 cm), Depth3 (14 – 20 cm), Depth4 (20 – 26 cm), Depth5 (26 – 32 cm), and Depth6 (32 – 37 cm), of loblolly pine seedlings during winter (January – March) and spring (March – May) in four sites in southern Arkansas.

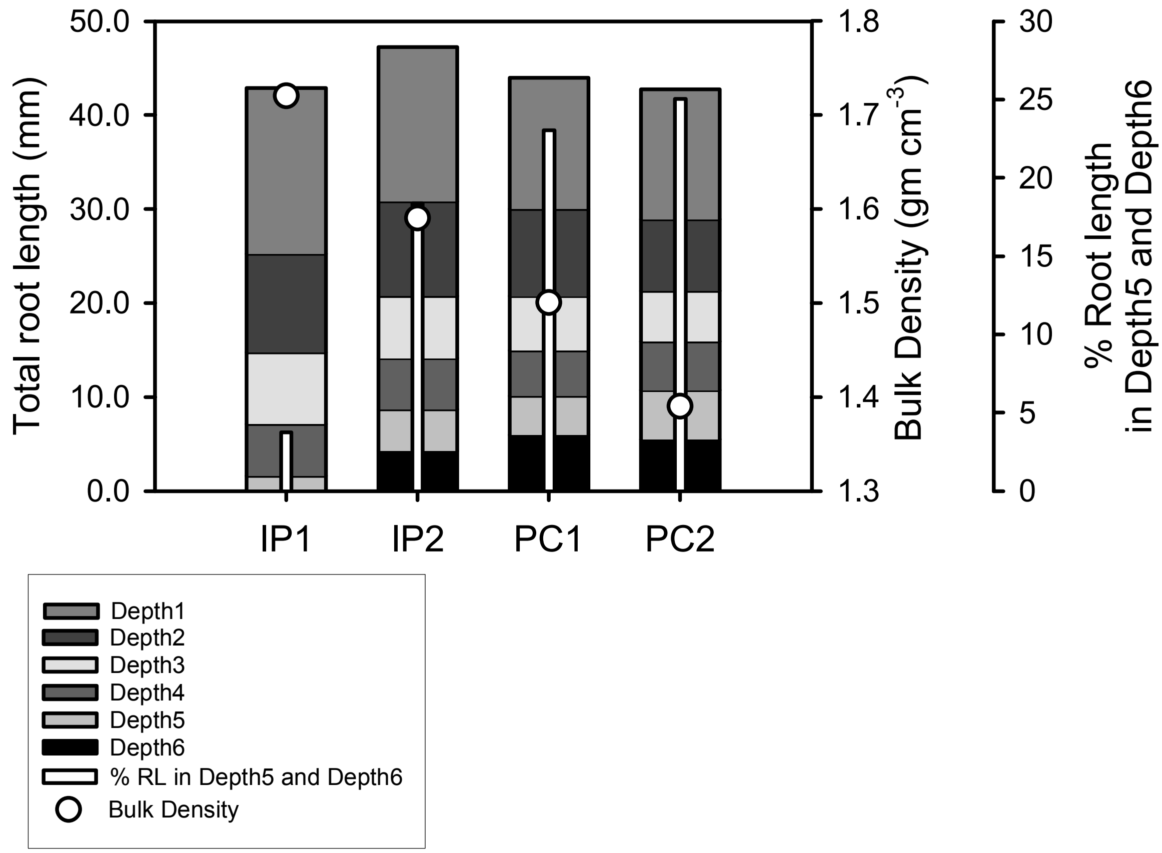

Figure 8. Total root length per frame for six depth classes [Depth1 (0 – 7 cm), Depth2 (7 – 14 cm), Depth3 (14 – 20 cm), Depth4 (20 – 26 cm), Depth5 (26 – 32 cm), and Depth6 (32 – 37 cm)], percentage of total root length in Depth5 and Depth6, and subsoil bulk density of four sites in southern Arkansas growing loblolly pine seedlings.

Conclusions

- Fertilization, chemical vegetation control, and mechanical site preparation had a positive effect on height and groundline growth. The effect of one treatment was additive to the other after two years of growth. Mechanical site preparation alone had a greater positive effect than did fertilization alone.

- Survival was not affected by treatment, although there was a substantial survival advantage from mechanical site preparation observed on sites with high bulk density. Winter waterlogging may be more detrimental for survival than summer droughts on the West Gulf flatwoods.

- Fertilization stimulates root growth more in shallow soil layers. Increased above-ground growth was found in conjunction with increased below-ground growth.

- Subsoil bulk density can greatly restrict root growth and consequently seedling growth and survival.

RESULTS AND DISCUSSION: WATER USE AND GAS EXCHANGE

Water potential (ψ)

Water potential was significantly affected by treatments in both growing seasons (1999 and 2000). Seedlings of HERB plots (FP-VF, BED-CV, and BED-CVF) had significantly higher ψ than the non-HERB plots (FP-N, BED-N, and BED-F) (Figures 9 and 10). During the 1999 growing season average seedling ψ for the HERB plots was -1.14 MPa compared to -1.45 MPa for seedlings of non-HERB plots. These values were -1.11 and -1.27 MPa for the 2000 growing season, respectively. Lowest average ψ was observed for BED-F seedlings in both growing seasons and lowest mean ψ for any treatment at any hour was found for BED-F (-2.1 MPa) in the August sampling session in 1999 at 1800 hours and for BED-N (-2.0 MPa) in the 2000 growing season in the August sampling session at 1800 hours.

Water potential was highest early in the morning and decreased throughout the day in all sessions (Figures 9 and 10). Seedling ψ at 0900 hours was comparable for treatments in the first sampling sessions in May in both growing seasons and for the June sampling session in 2000. However, later in the summer ψ was significantly higher at 0900 hours for HERB plots. Water potential at 0900 hours also decreased as the season progressed. Average seedling ψ at 0900 hours in the May sampling session in 1999 was -0.58 MPa and in the August sampling session was -0.98 MPa. These values were -0.61 MPa and -0.76 MPa for the same months in the 2000 growing season, respectively. This trend was also measured at other hours because a progressive drought was observed with both seasons. Water potential for the first sampling session in 1999 averaged for all treatments was -1.15 MPa whereas for the last sampling session in August this was -1.50 MPa. During the 2000 growing season water potential dropped from an average -1.16 MPa for all

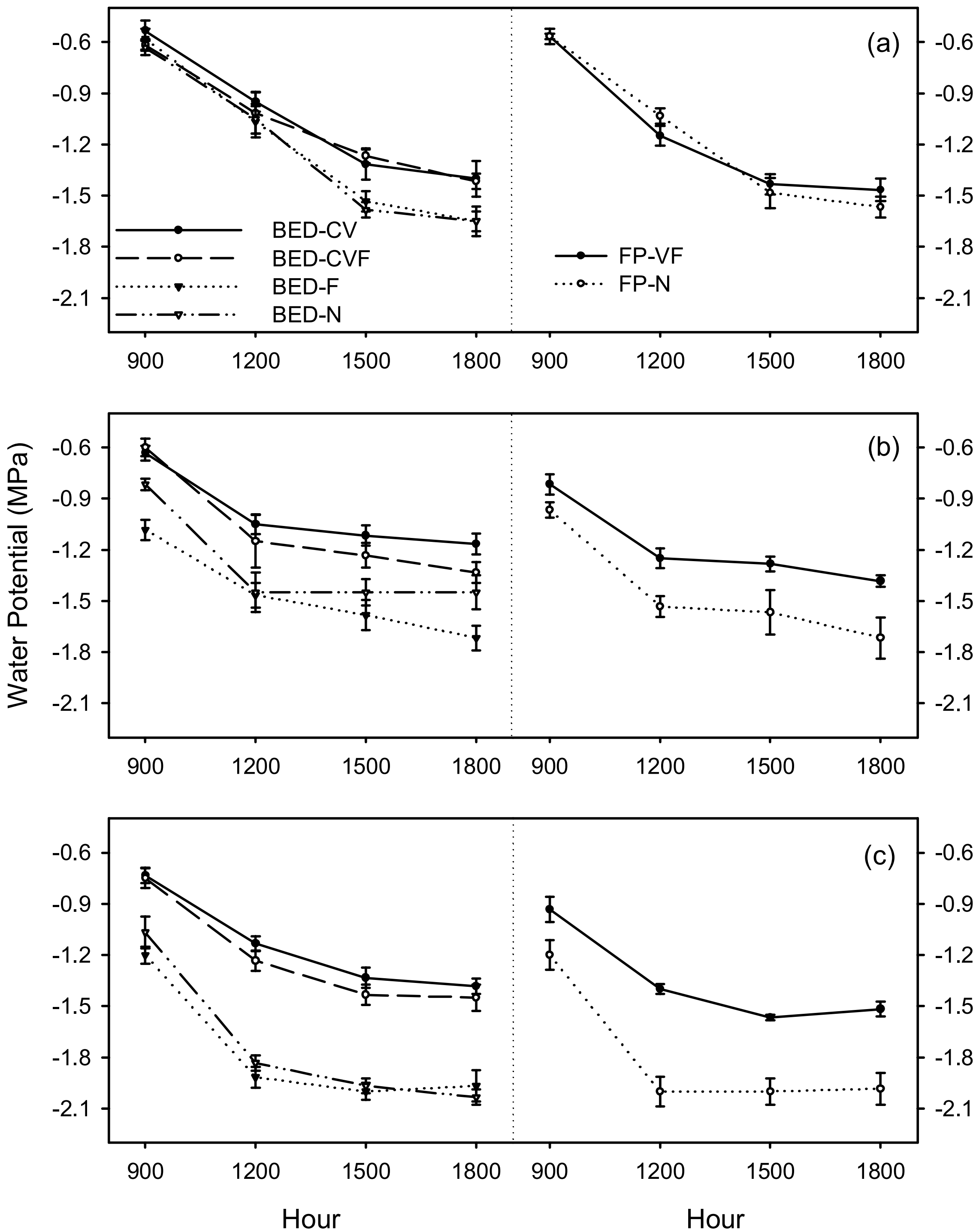

Figure 9. Loblolly pine seedling water potential on a site near Crossett, AR on May 18 (a), July 1 (b) and August 21 (c) in 1999 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

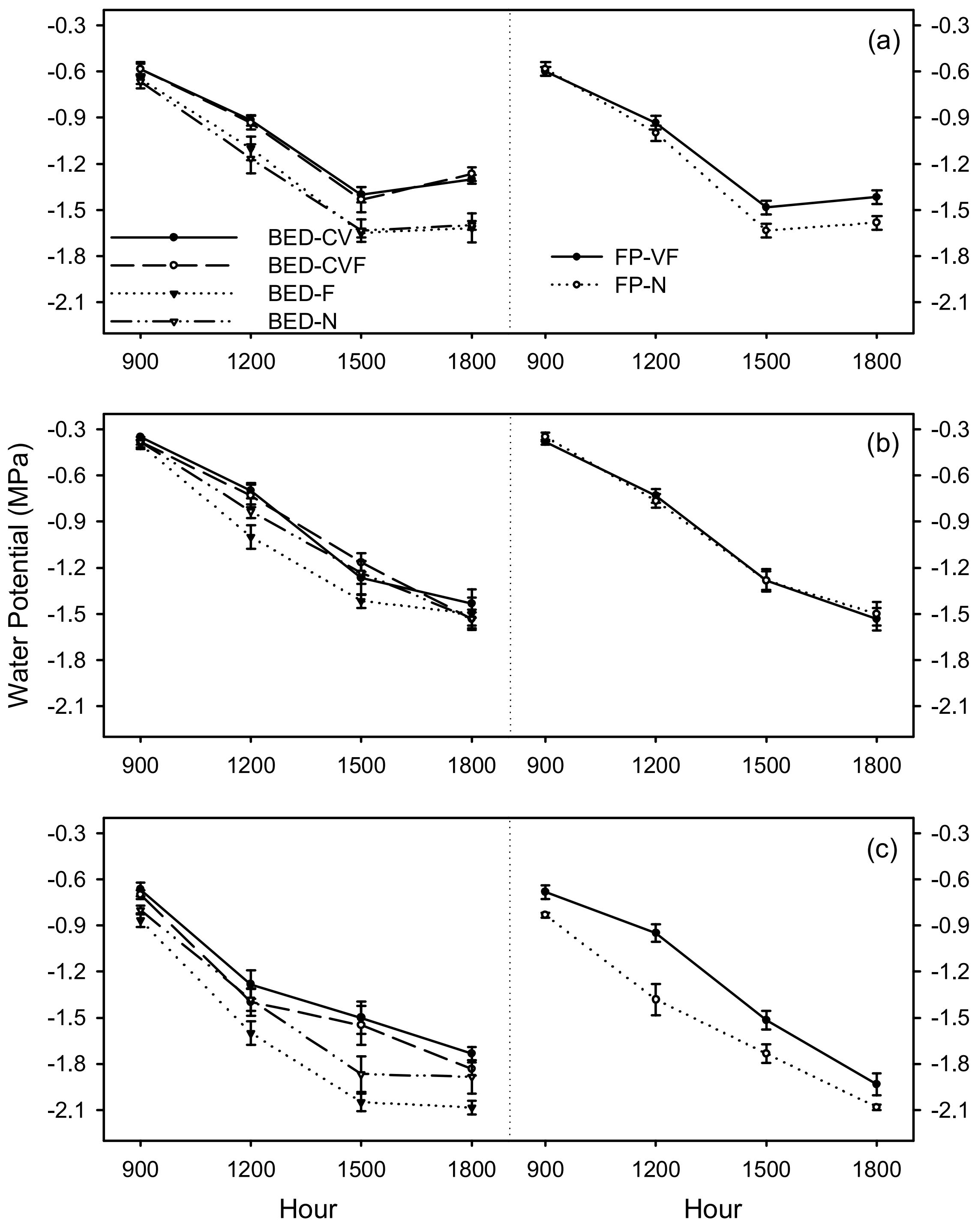

Figure 10. Loblolly pine seedling water potential on a site near Crossett, AR on May 9 (a), June 8 (b), and August 18 (c) in 2000 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

seedlings in May to -1.43 MPa in August. This can perhaps be best explained by rainfall and available soil moisture. While rainfall data were not collected on the site and available only from a nearby weather station in Crossett, AR, soil volumetric moisture content (VMC) data reflect this relationship between progressive drought and decreased seedling water potential. Drought here is defined as an extended period of deficient rainfall causing water stress in plants. During the 1999 growing season soil VMC in the upper 15 cm decreased from an average 20.4% for all plots in May to 6.5% in August and in the 2000 growing season decreased from 18.4% to 5.6% for the same months, respectively (Figure 11).

Soil VMC was comparable among all treatments during the first sampling session in May in both growing seasons. However, in the following sampling sessions in both 1999 and 2000, soil VMC was found significantly higher for plots treated with chemical vegetation control.

Soil VMC for the FLAT plots was significantly lower in the last two sampling sessions in 1999 growing season, but was higher in the last two sampling sessions in 2000 growing season (Figure 11). However, this did not result in any significant differences in seedling ψ for any of these sampling sessions.

The use of fertilization visibly enhanced interspecific competition. However, this did not relate to any significant effect on seedling ψ due to fertilization although seedling ψ for BED-F plot was always the lowest in both growing seasons.

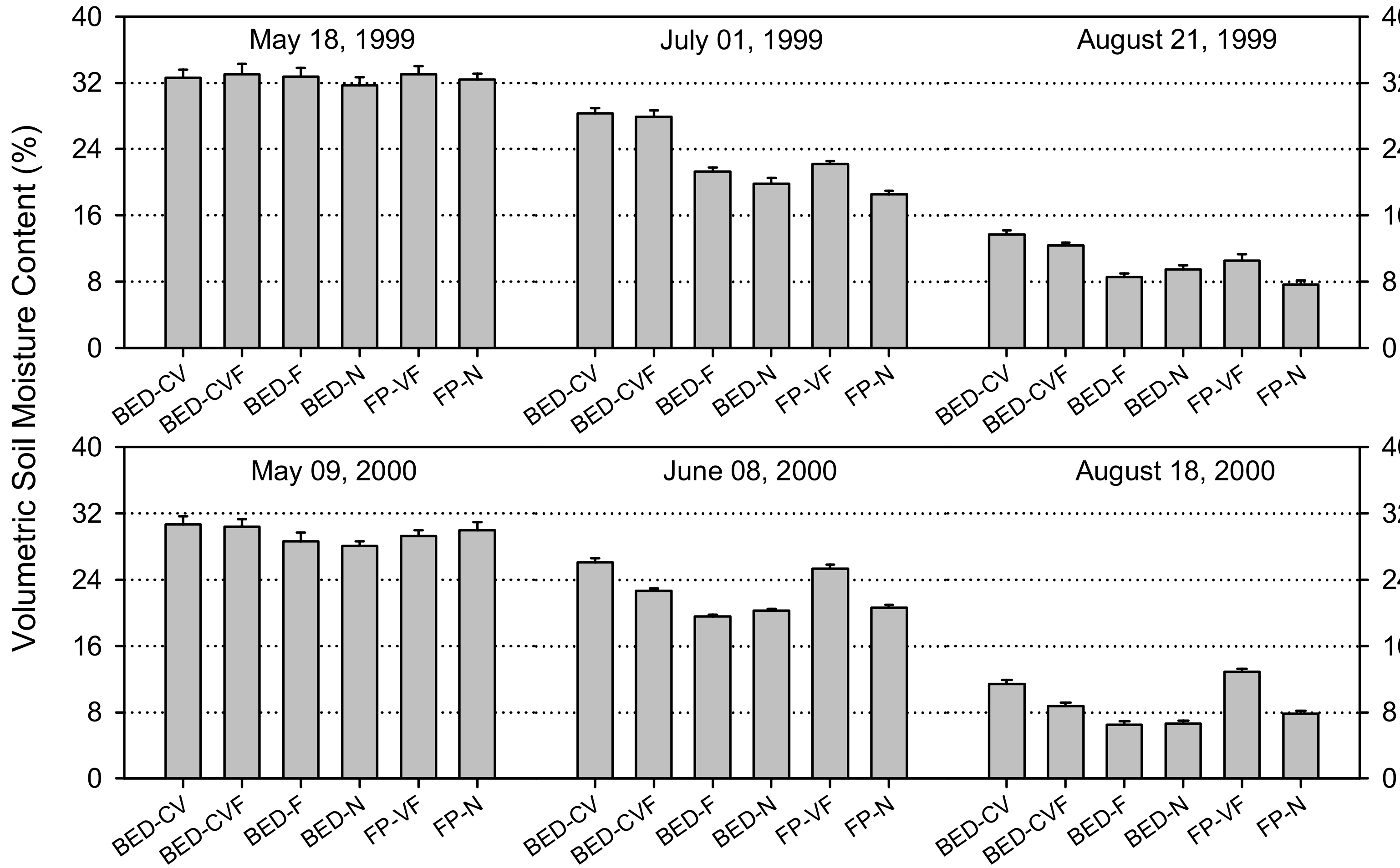

Figure 11. Volumetric soil moisture content (0-15 cm) of a site near Crossett, AR on three different sampling sessions in 1999 and 2000 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

Stomatal Conductance (g_s)

Stomatal conductance was significantly affected by treatments in both growing seasons. Seedlings of HERB plots had higher g_s than the others (Figures 12 and 13). Average g_s during the 1999 growing season for these plots was 0.41 cm/s compared to 0.35 cm/s for the non-HERB plots. These values were 0.24 cm/s and 0.22 cm/s for the 2000 growing season, respectively. Stomatal conductance was not affected by fertilization or mechanical site preparation in either growing season.

During both 1999 and 2000 growing seasons, seedling g_s was maximum at 1200 hours and 1500 hours. Seedlings conducted more water early in the summer when soil moisture was higher (Figure 11) and needle water potential was greater (Figures 9 and 10) compared to late summer. Average seedling g_s in the first sampling session in May, 1999 was 0.53 cm/s whereas for the last sampling session (August, 1999) this was 0.21 cm/s. These values were 0.42 cm/s and 0.13 cm/s for the 2000 growing season, respectively.

During the last sampling session on August 18, 2000 (Figure 13), g_s started to cease at 1500 hours for BED-F seedlings and at 1800 hours for BED-N seedlings. This was related to the low water potential for these seedlings, however no index point for ψ was observed for stomatal closure. Overall g_s for this sampling session was lower for all treatments (0.13 cm/s).

Transpiration (E)

Transpiration was not affected by treatments in the 1999 growing season; although, when means of HERB plots were compared to the rest, E was significantly higher for the former. Transpiration was significantly affected by treatments in the 2000 growing season and found higher for HERB treatments.

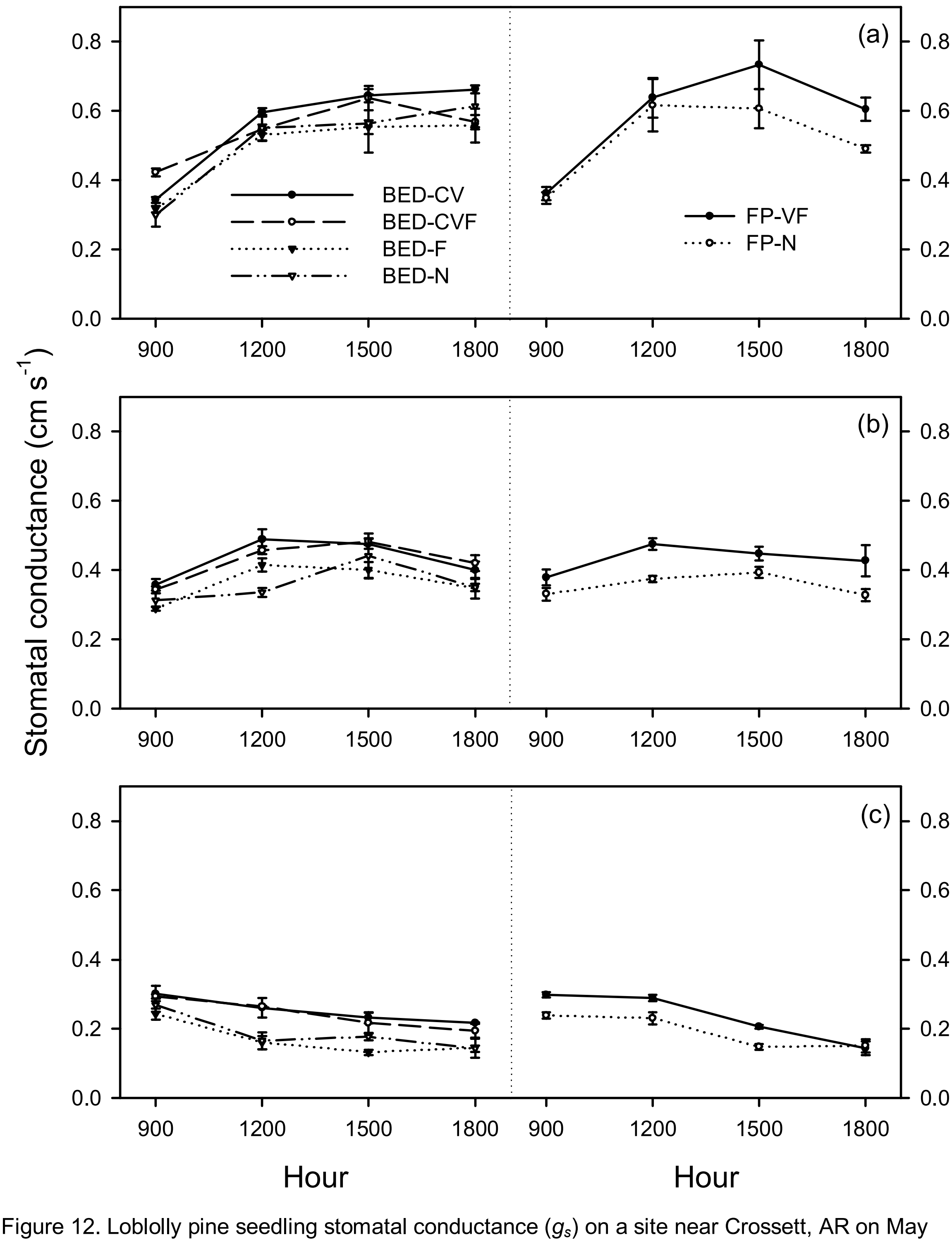

Figure 12. Loblolly pine seedling stomatal conductance (g_s) on a site near Crossett, AR on May 18 (a), July 1 (b), and August 21 (c) in 1999 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

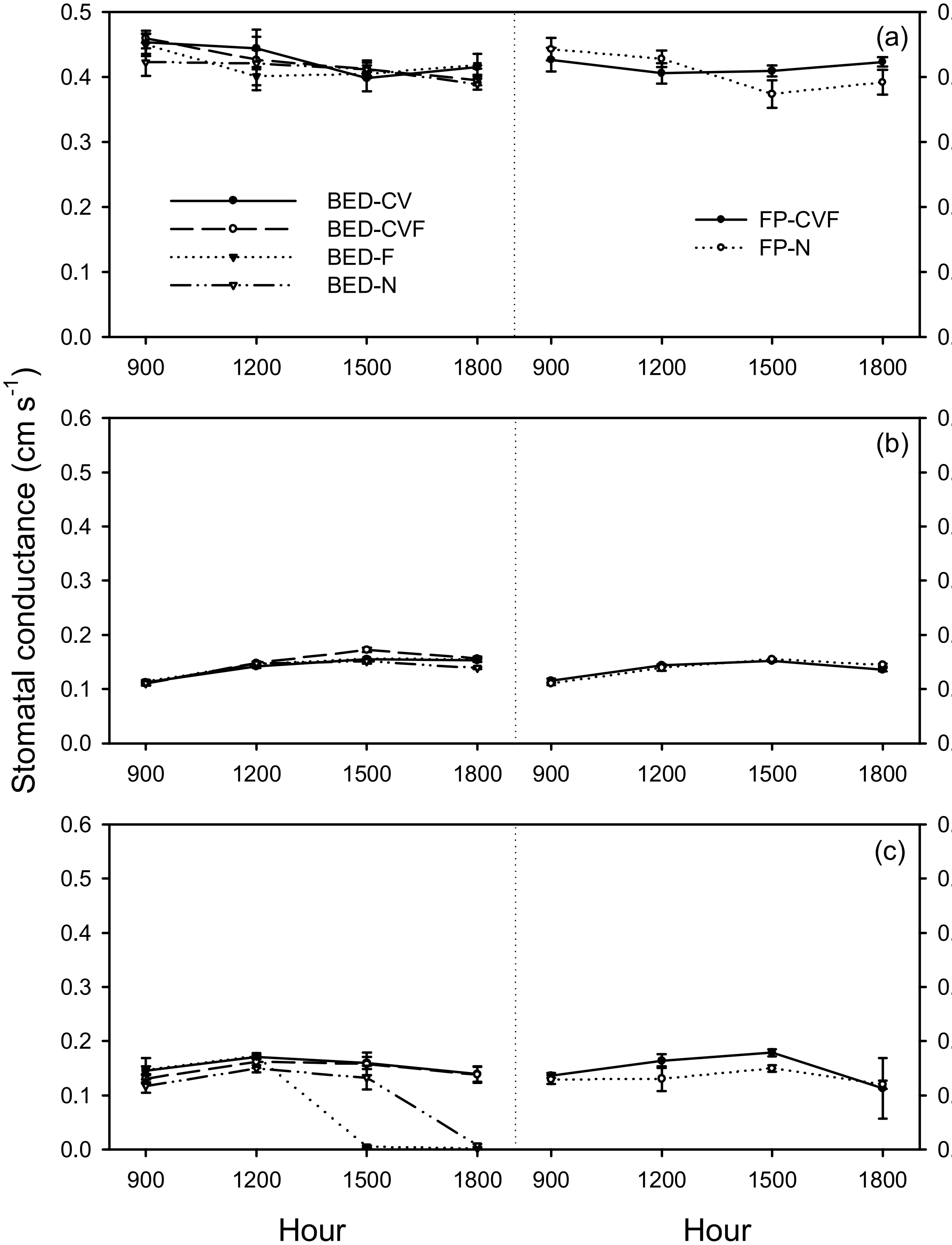

Figure 13. Loblolly pine seedling stomatal conductance (g_s) on a site near Crossett, AR on May 9 (a), June 8 (b), and August 18 (c) in 2000 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

Average E during the 1999 session for HERB and non-HERB plots was 0.0041 and 0.0039 mol m^{-2} s^{-1}, respectively. Transpiration values for these two groups of treatments plots during the 2000 growing season were 0.0027 and 0.0023 mol m^{-2} s^{-1}, respectively. Transpiration was not affected by fertilization or mechanical site preparation during the 1999 and 2000 growing seasons.

Transpiration was lowest in the early morning at 0900 hours during both growing seasons and reached a maximum at 1500 hours after which it declined (Figures 14 and 15). During the last sampling session in the 2000 growing season, E ceased for BED-F at 1500 hours and for BED-N at 1800 hours (Figure 15-c), on the same seedlings at the same hours with ceased stomatal conductance (Figure 13-c). Transpiration significantly decreased among sampling sessions during the 1999 growing session and remained comparable between the first two sampling sessions in 2000 after which it significantly decreased in the last sampling session (August). Despite increasing vapor pressure deficit (VPD) from early summer in the May sampling sessions in 1999 (VPD = 18.2 mb) and 2000 (VPD = 18.9 mb) to late summer in the August sampling sessions (VPD = 38.09 and 34.70 mb in 1999 and 2000, respectively), seedling transpiration rate decreased suggesting that VPD effect on transpiration may be controlled by water potential at different level of seedling water stress.

Photosynthesis (A_n)

Net photosynthesis was not affected by treatments in the 1999 growing season, although BED-CVF had significantly greater A_n than the other treatments in the 2000 growing season. Average A_n for the 1999 and 2000 growing seasons were 4.92 and 4.35 μmol m^{-2} s^{-1}. Photsynthesis was highest early in the growing season and decreased as the season progressed. During the 1999 growing season, A_n was 5.64, 4.98 and 4.14 μmol m^{-2} s^{-1} for the May, July and August

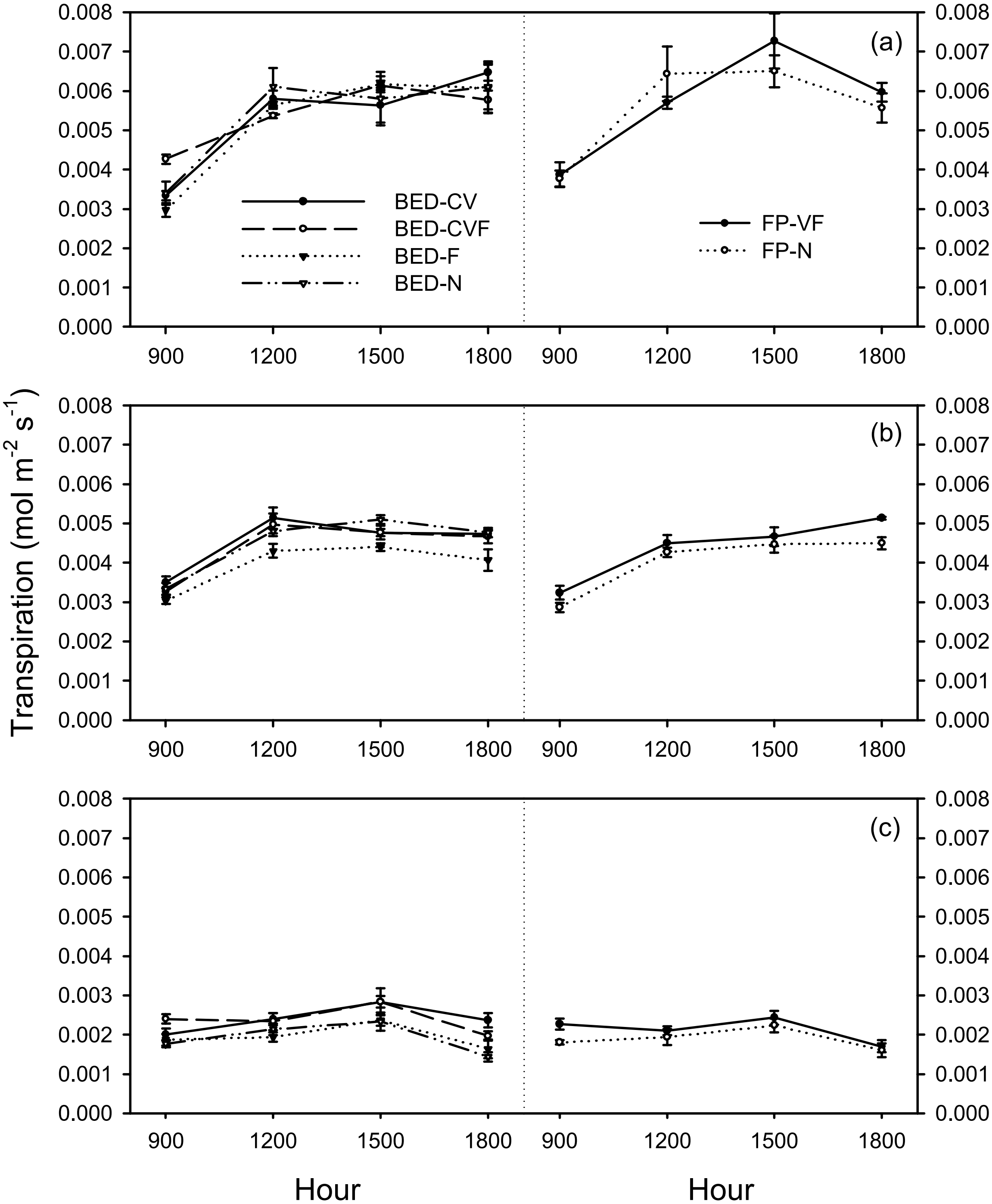

Figure 14. Loblolly pine seedling transpiration (*E*) on a site near Crossett, AR on May 18 (a), July 1 (b), and August 21 (c) in 1999 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

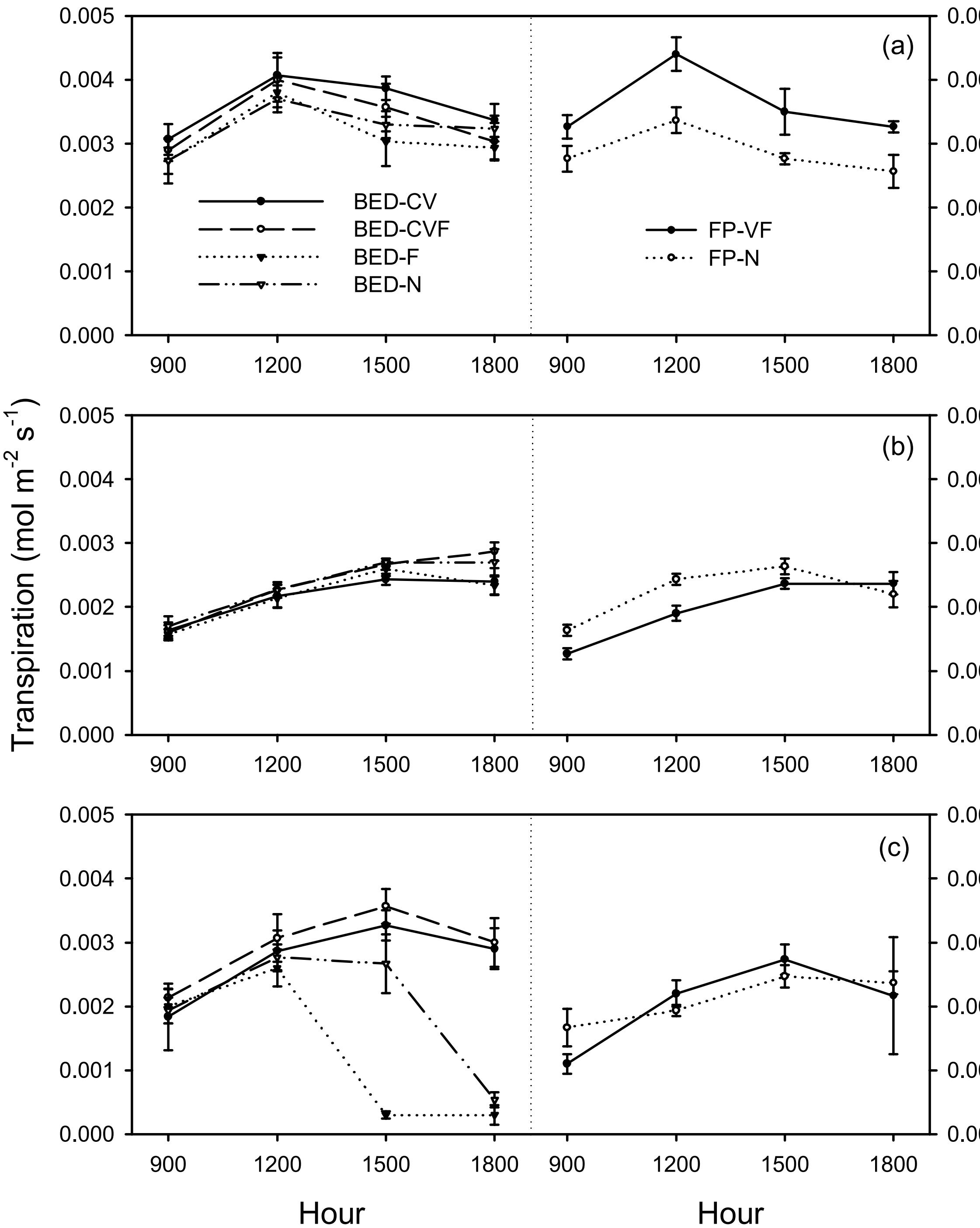

Figure 15. Loblolly pine seedling transpiration (*E*) on a site near Crossett, AR on May 9 (a), June 8 (b), and August 18 (c) in 2000 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

sampling sessions, respectively (Figure 16). These values were 5.68, 4.04, and 3.33 μmol m^{-2} s^{-1} for the May, June and August sampling sessions in the 2000 growing season, respectively (Figure 17).

During the 2000 growing season, seedlings of HERB plots had significantly greater A_n than the non-HERB plots. This was due to continued seedling g_s on HERB plots observed in the August, 2000 sampling session (Figure 13), whereas BED-F and BED-N seedlings failed to photosynthesize when their g_s ceased (Figure 17).

Chemical vegetation control provided more soil water to the seedlings throughout the 1999 growing season leading to significantly lower water use efficiency (WUE) for the HERB seedlings. These seedlings had the luxury of conducting more water leading to increased transpiration and continued photosynthesis at time of water stress. During the 1999 growing season, HERB seedlings had an average WUE of 3.34 mg CO_2 / gm H_2O compared to 3.66 mg CO_2 / gm H_2O for the non-HERB seedlings. During the 2000 growing season, WUE was calculated excluding the seedlings which experienced ceased stomatal conductance in the August sampling session, and was non-significantly ($P = 0.27$) lower for HERB seedlings at 4.24, compared to 4.40 mg CO_2 / gm H_2O for non-HERB seedlings. Water use efficiency was highest at 0900 hours in both growing seasons due to high net photosynthesis and low transpirational water loss at this hour. On the contrary, WUE was lower during the 1200 and 1500 hours due to enhanced transpirational water loss at these hours resulting from high VPD.

There was higher precipitation in 2000 than in 1999. Precipitation data were collected from a nearby weather station (source: NCDC online data at http://www.ncdc.noaa.gov/oa/climate/climatedata.html) and showed that during

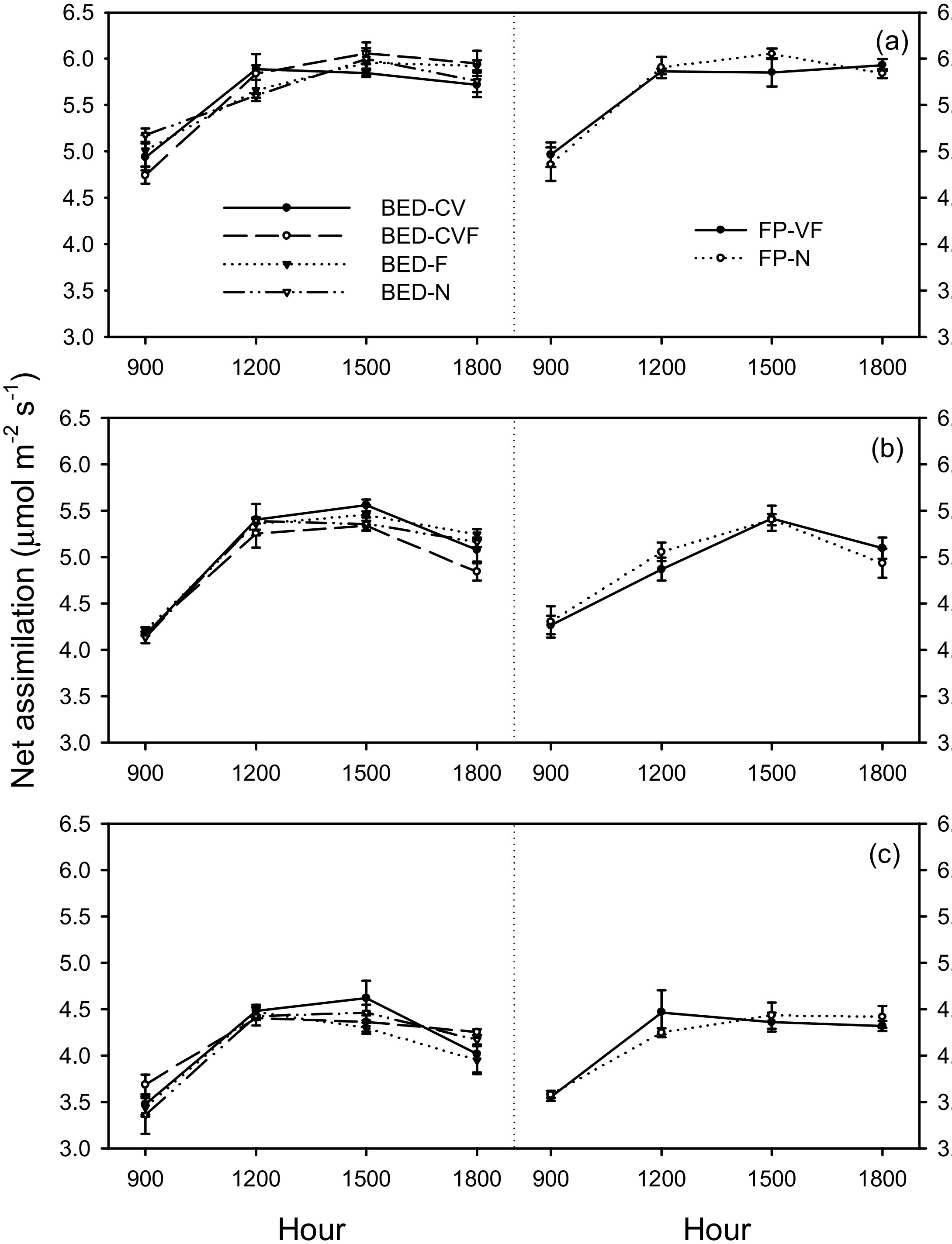

Figure 16. Net assimilation rate (A_n) of loblolly pine seedlings on a site near Crossett, AR on May 18 (a), July 1 (b), and August 21 (c) in 1999 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

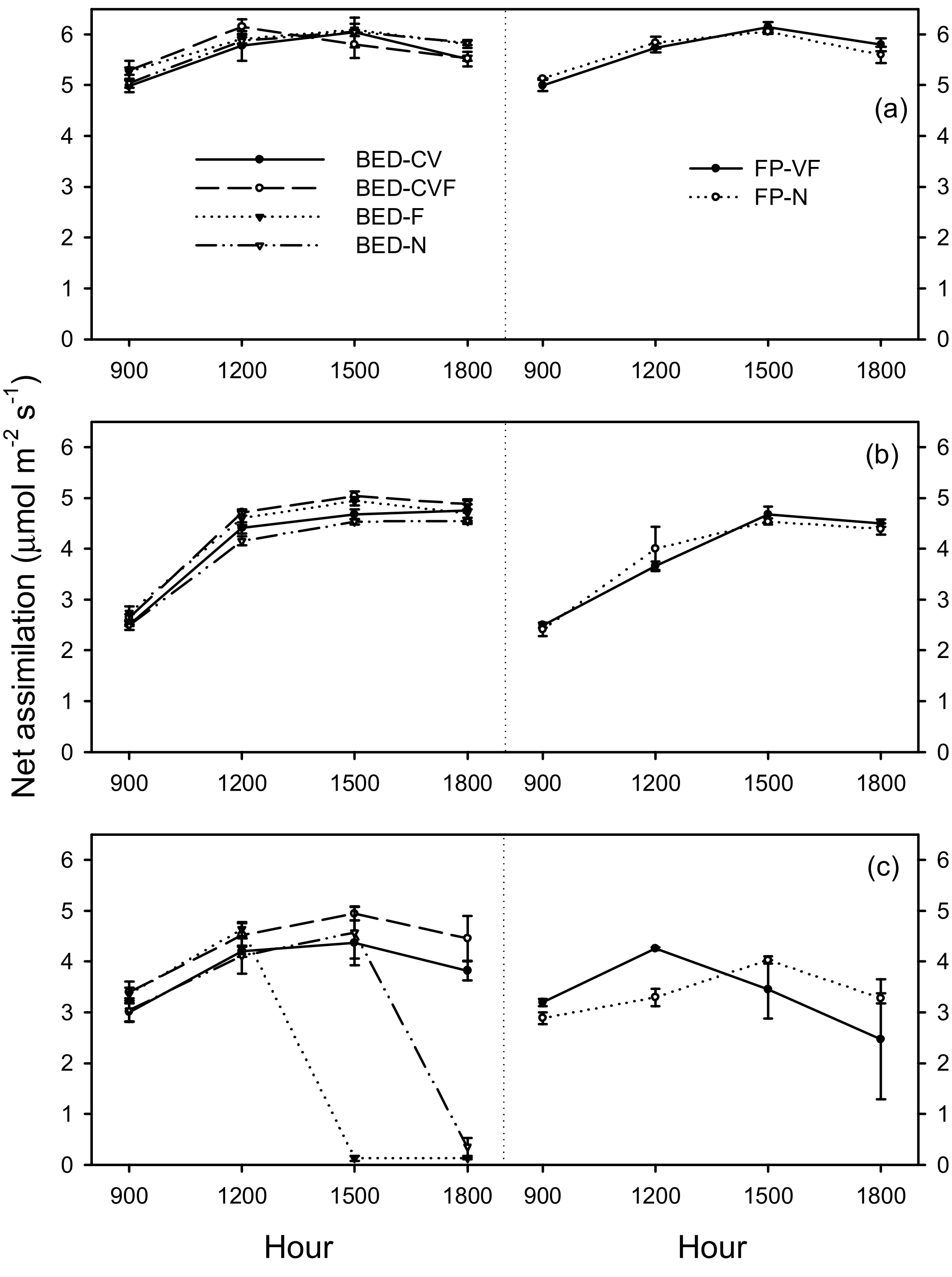

Figure 17. Net assimilation rate (A_n) of loblolly pine seedling on a site near Crossett, AR on May 9 (a), June 8 (b), and August 18 (c) in 2000 from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first year fertilization and complete vegetation control (FP-VF). Vertical bars indicate one standard error.

the 1999 and 2000 growing seasons, there were 117.2 and 138.6 cm of rain, respectively. Of this rainfall, 50.2 and 59.7 cm were collected between April and September in the 1999 and 2000 growing seasons, respectively. Higher precipitation in the 2000 growing season led to a higher average seedling ψ for this growing season (-1.30 MPa in 1999 and -1.19 MPa in 2000). Also ψ at 0900 hours was not improved by chemical vegetation control until the August sampling session in the 2000 growing season, whereas in the 1999 growing season HERB seedlings had significantly higher ψ as early as July. During both growing seasons, soil water potential was high until mid-summer and standing water was seen on the site at lower spots suggesting that water stress may be a problem on these flatwoods for only the latter part of the summer. Although herbaceous competition may appear during the late spring and occupy the site in early summer, there can still be available water from spring waterlogging to reduce competition for moisture. Timber growers in the Western Gulf flatwoods can achieve comparable advantage from chemical herbicides sprayed in mid-summer in case early summer application was delayed unless there are obvious indications of early summer stress from less precipitation.

Conclusions

- Chemical herbaceous vegetation control improved seedling water potential.

- Enhanced evapotranspiration during the growing season did not dry out soil from winter waterlogging until mid-summer and the effect of chemical vegetation control on seedling water status did not show until late summer. Therefore, timber growers in the West Gulf flatwoods can gain comparable benefits from late summer applications of chemical herbicides. However, the economics of added benefit from herbicide on these sites need to be evaluated before large-scale use.

- The combined use of chemical vegetation control and fertilization (BED-CVF) yielded higher net photosynthesis than in other treatments. This resulted from continued seedling net photosynthesis during the time of severe stress for this treatment, perhaps what have contributed to their maximum growth.

RESULTS AND DISCUSSION: FATE OF APPLIED FERTILIZERS - SUBSOIL LEACHING LOSS AND NUTRIENT CONTENT IN THE LIVE FOLIAGE

Nitrogen

Nitrogen (total N) concentration in the soil solution, averaged for all sampling sessions, did not differ significantly between treatments (BED-F and BED-N) in the 1998-sites, although it was higher for BED-F at 276.91 μmol L^{-1} compared to 220.5 μmol L^{-1} for BED-N. In the 1999 sites, BED-F had the highest N concentration and significantly more (> 240%) than FP-N (Table 4). However, no general trend for higher N loss due to fertilization ($P = 0.48$), chemical vegetation control ($P = 0.80$) or mechanical site preparation ($P = 0.63$) was observed on these sites.

Table 4. Nutrient concentration of soil solution derived from suction-cup lysimeters installed on bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on 10 sites in southern Arkansas. Data followed by same letter within column in same plantation year are not significantly different at $\alpha = 0.05$.

	Treatment	N	P	K	Ca	Mg
		(μmol L^{-1})				
1998-Sites	BED-F	276.91 a	1.28 a	19.33 a	46.71 a	48.89 a
	BED-N	220.50 a	1.50 a	18.35 a	51.53 a	26.00 b
1999-Sites	BED-CV	94.85 ab	1.51 c	20.15 c	61.31 a	36.36 b
	BED-CVF	92.40 ab	2.56 a	26.42 bc	42.66 ab	55.13 a
	BED-F	118.95 a	2.26 ab	32.26 b	68.57 a	61.71 a
	BED-N	81.62 ab	2.13 abc	20.90 c	29.34 b	27.13 b
	FP-N	49.91 b	2.16 abc	21.15 c	33.31 b	34.34 b
	FP-VF	96.20 ab	1.58 bc	43.71 a	66.82 a	56.72 a

Nitrogen concentration in the soil solution increased after the first fertilization until the following spring and gradually decreased to a negligible amount thereafter despite further fertilizer application (Figure 18). In the 1998 sites, N concentration was highest during the Jan-1999 sampling session and averaged 702.42 μmol L^{-1} compared to the lowest in Feb-2000 at 2.07 μmol L^{-1}. For the 1999 sites, highest and lowest values were observed in Jul-1999 (242.65 μmol L^{-1}) and Jan-2001 (2.72 μmol L^{-1}), respectively (Figure 19). Segal et al. (1987) also reported similar trends of soil solution N concentration on Florida flatwoods.

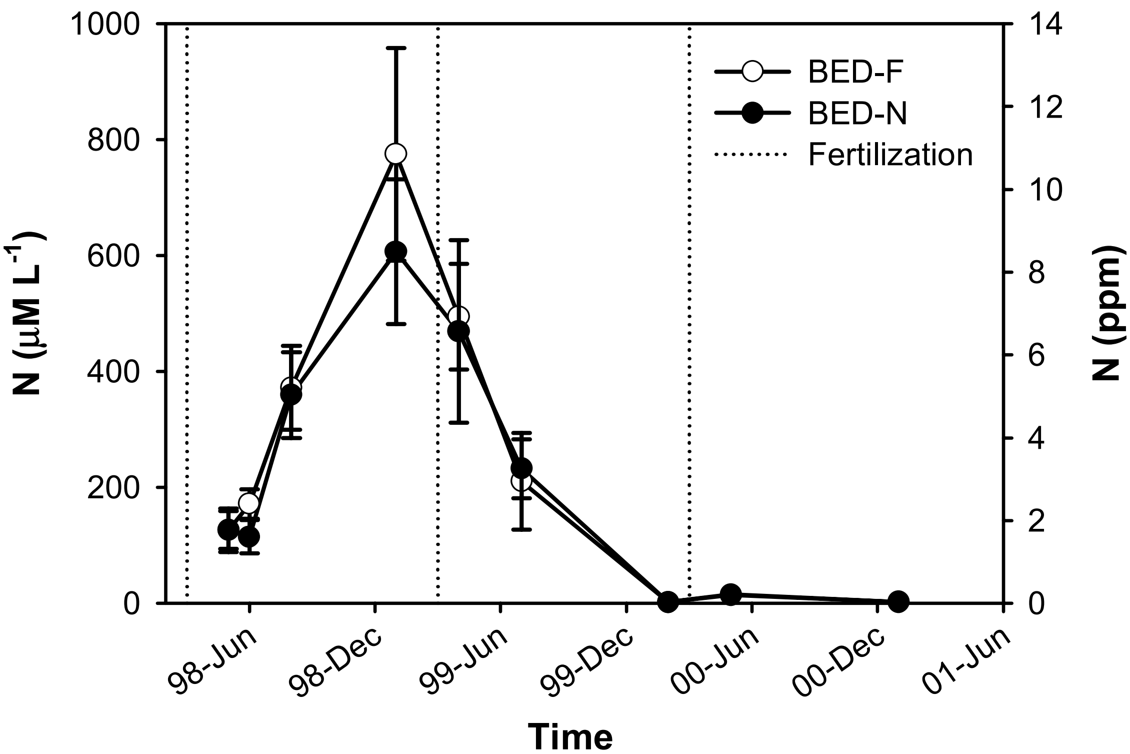

Figure 18. Mean nitrogen concentration in the soil solution from suction cup lysimeters installed at fragipan depth from different treatments: bedding control (BED-N) and bedding plus continuous fertilization (BED-F) on four sites planted in 1998 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

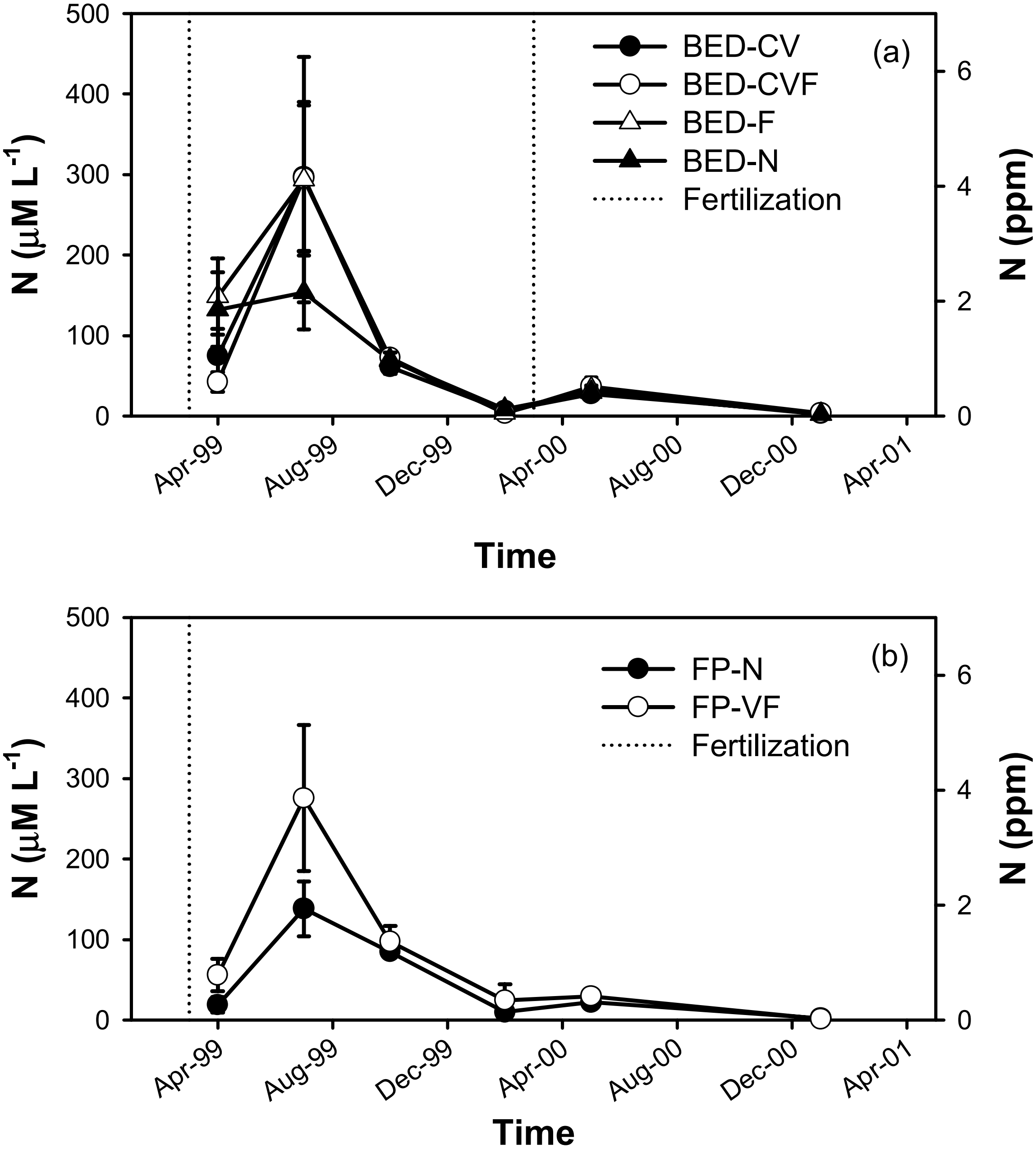

Figure 19. Mean nitrogen concentration in the soil solution from suction cup lysimeters installed at fragipan depth from four bedding treatments (a): bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF) and two flatplanting treatments (b): flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on six sites planted in 1999 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

Seasonal increases of N concentration on both fertilized and non-fertilized plots have been observed by other investigators (Morris and Pritchett 1982, Peterjohn and Correll 1983, Lowerance et al. 1984). This could be primarily due to stimulation from pronounced seasonal wetting and drying (Morris and Pritchett 1982), or enhanced N mineralization of forest floor litter and high soil temperatures (Peterjohn and Correll 1983, Lowerance et al. 1984). However, in this study no increase in N concentration was observed in succeeding years despite repeated fertilizer application for one additional year in BED-F and BED-CVF plots in the 1999 sites and two additional years in BED-F plots in the 1998 sites following first-year fertilization. This may be due to increased demand for N by the growing vegetation in the later years and subsequently more N allocation to the green foliage and less leaching loss to the subsoil.

Phosphorus

Phosphorus (total P) concentration in the soil solution samples was comparable for BED-F and BED-N in the 1998 sites. Average P concentrations across all sampling sessions for BED-F and BED-N plots on these sites were 1.28 and 1.50 $\mu mol\ L^{-1}$, respectively. There was a significant treatment effect for P concentration in the soil solution in the 1999 sites with BED-CVF having the highest value (Table 4). However, no significant effect due to fertilization, chemical vegetation control or mechanical site preparation was found. Phosphorus concentration usually peaked in the summer and was low in spring, possibly a dilution effect of soil solution (Figures 20 and 21). However, P concentration was usually low throughout the entire year. Phosphorus is highly immobile in soil solution and moves primarily by diffusion, perhaps the reason why most investigators found no significant phosphorus leaching to the subsoil (Morris and Pritchett 1982, Peterjohn and Correll 1983, Lowerance et al. 1984).

Potassium

Potassium concentration did not differ significantly among the 1998 site treatments (BED-F and BED-N). Average K concentrations in the soil solution across all sampling sessions and sites for these treatments were 19.33 and 18.35 µmol L^{-1}, respectively. There was a treatment effect on K concentration in the soil solution among the 1999 sites. Fertilization significantly increased K concentration and the FERT treatments had the highest value for K concentration across all sampling sessions. Average K concentration for FERT plots was

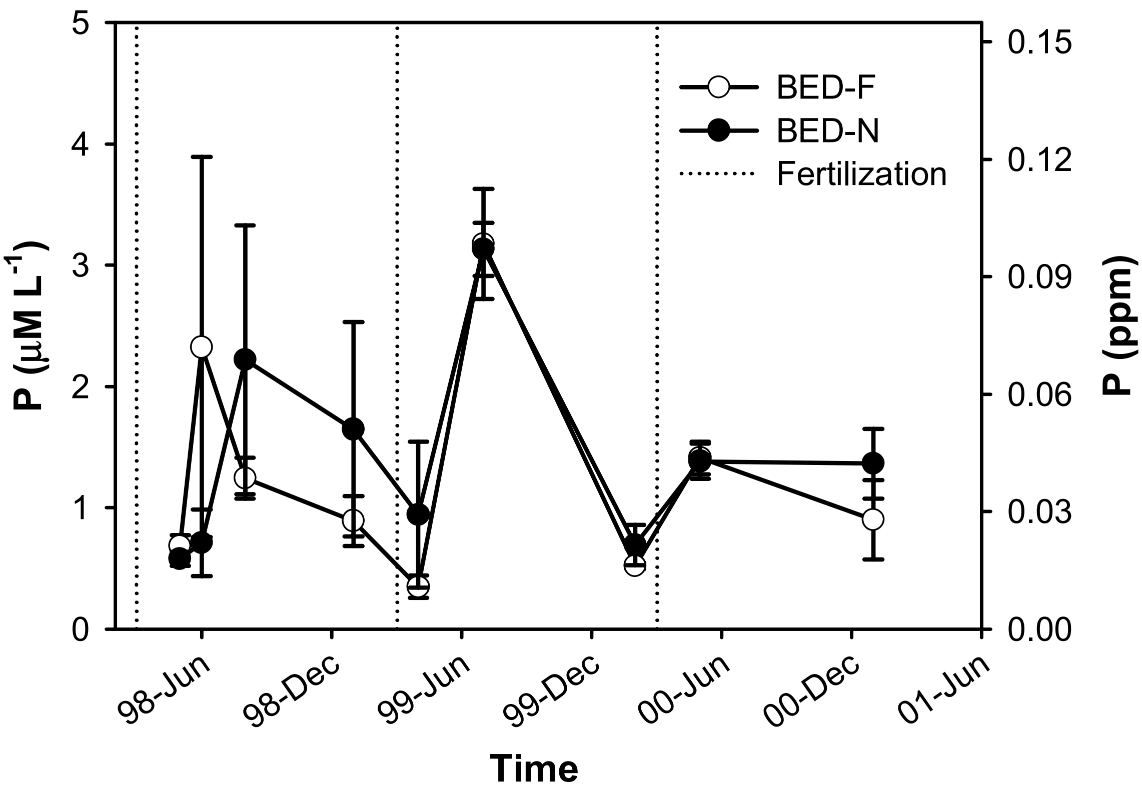

Figure 20. Mean phosphorus concentration in the soil solution from suction cup lysimeters installed at fragipan depth from different treatments: bedding control (BED-N) and bedding plus continuous fertilization (BED-F) on four sites planted in 1998 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

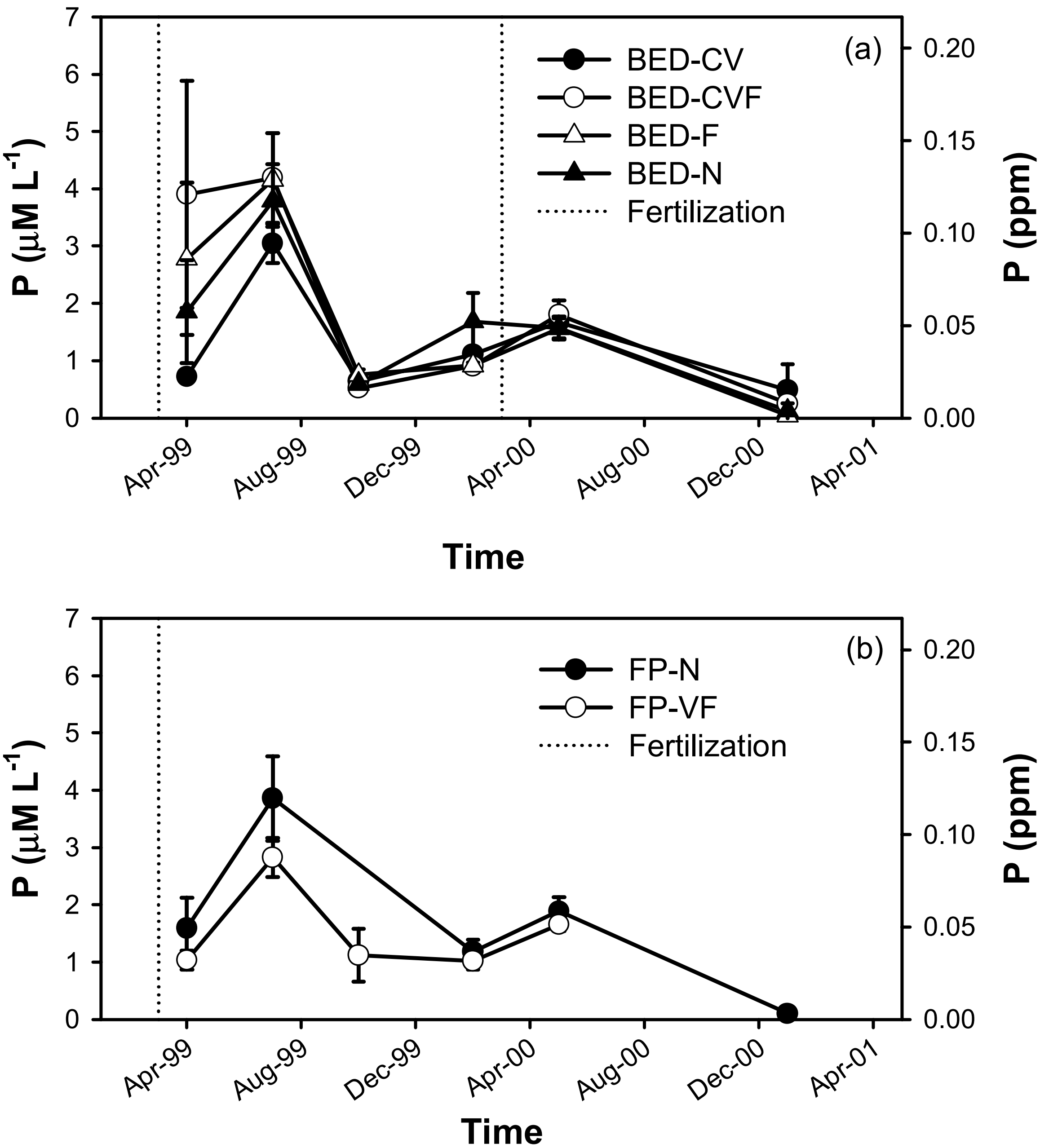

Figure 21. Mean phosphorus concentration in the soil solution from suction cup lysimeters installed at fragipan depth from four bedding treatments (a): bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF) and two flatplanting treatments (b): flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on six sites planted in 1999 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

34.1 μmol L^{-1} compared to 20.7 μmol L^{-1} for non-FERT plots. Potassium is very mobile in the forest ecosystem (Morris and Pritchett 1982) and leaches significantly more after fertilization (Lowerance et al. 1984). Potassium concentration showed a seasonal change with high concentration in early summer followed by a gradual decrease through December (Figures 22 and 23). Similar trends were observed by Lowerance et al. (1984) and Segal et al. (1987).

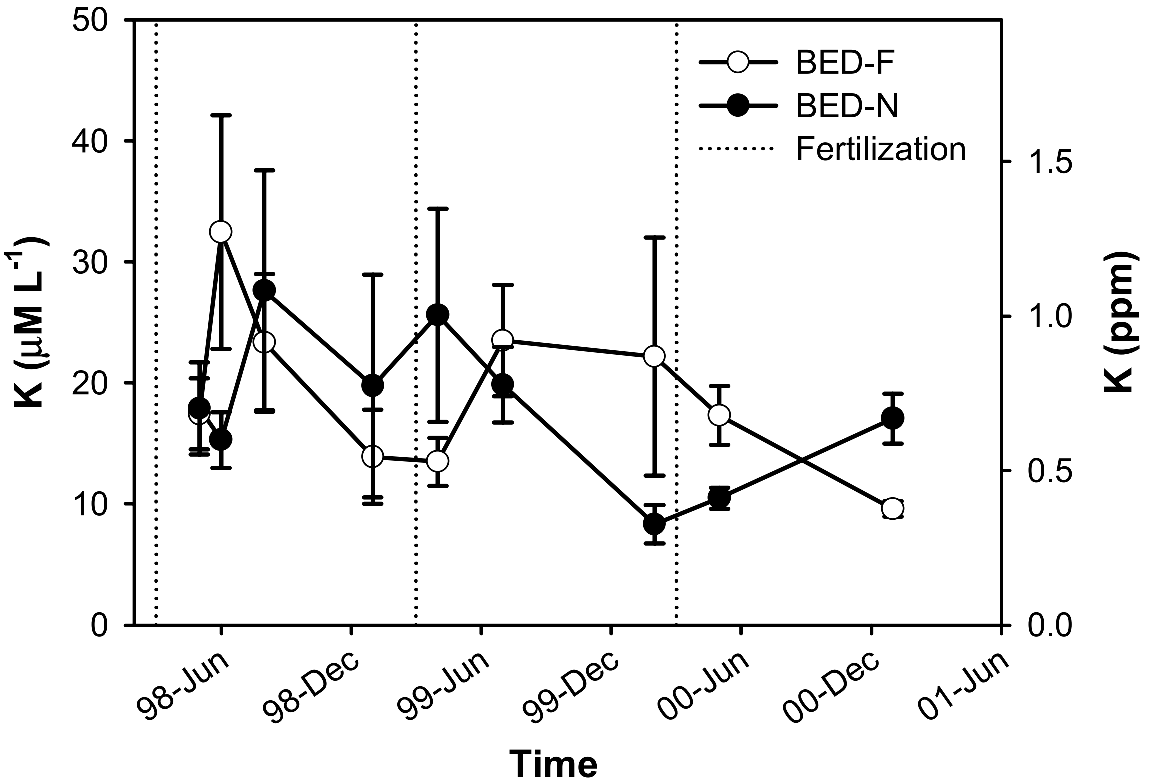

Figure 22. Mean potassium concentration in the soil solution from suction cup lysimeters installed at fragipan depth from different treatments: bedding control (BED-N) and bedding plus continuous fertilization (BED-F) on four sites planted in 1998 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

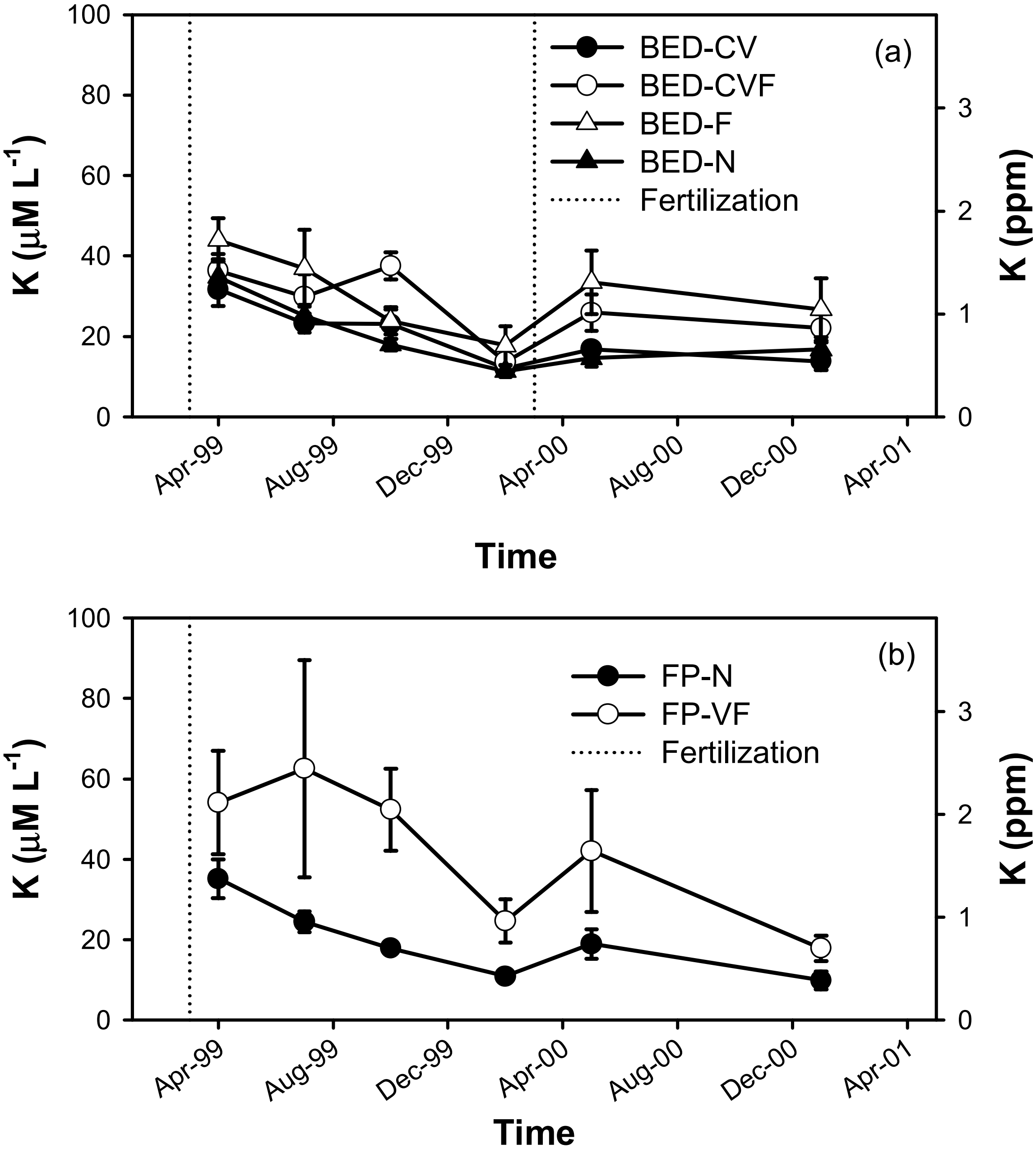

Figure 23. Mean potassium concentration in the soil solution from suction cup lysimeters installed at fragipan depth from four bedding treatments (a): bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF) and two flatplanting treatments (b): flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on six sites planted in 1999 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

Calcium

Calcium leaching loss was not significantly affected by treatments on the 1998 sites. Calcium concentration was highest for BED-F and lowest for FP-N in the 1999 sites (Table 4). Calcium concentration was high in February 2000 and January 2001 for all sites and also high in April 1999 for 1998 sites (Figures 24 and 25). High Ca concentration in soil solution at time of soil saturation has been reported by other investigators (Ponnamperuma 1972). Soils of West Gulf flatwoods are usually submerged during winter resulting in an anaerobic situation when more mobile, reduced Fe^{++}, Mn^{++}, and NH_4^+ become available which can displace Ca^{++} from the exchange sites (Segal et al. 1987).

Magnesium

Magnesium concentration was significantly affected by treatments in both 1998 and 1999 sites. In the 1998 sites, Mg concentration was 48.89 μmol L^{-1} for BED-F compared to 26.00 μmol L^{-1} for BED-N (Table 4). In the 1999 sites, Mg concentration for the FERT plots was 57.85 μmol L^{-1} compared to 32.63 μmol L^{-1} for the non-FERT plots. Concentration was higher during the wet winter in the 1998 sites, similar to the pattern observed for Ca (Figure 26). However, there was no seasonal trend observed for Mg concentration in the 1999 sites (Figure 27).

The difference in nutrient leaching due to fertilization was found in higher degrees in the unbedded plots compared to the mechanically site prepared plots (Figures 19, 21, 23, 25, and 27). Although FP-VF received fertilization only at the year of planting, these plots had consistently higher nutrient leaching, except for P, to the subsoil than the FP-N. This effect was present in the second year (2000) as well despite the fact that both FP-VF and FP-N were not fertilized in that year. This can best be explained by the fact that flatplanted plots had lower growth than the bedded plots, resulting in less usage of applied fertilizer and continued leaching loss.

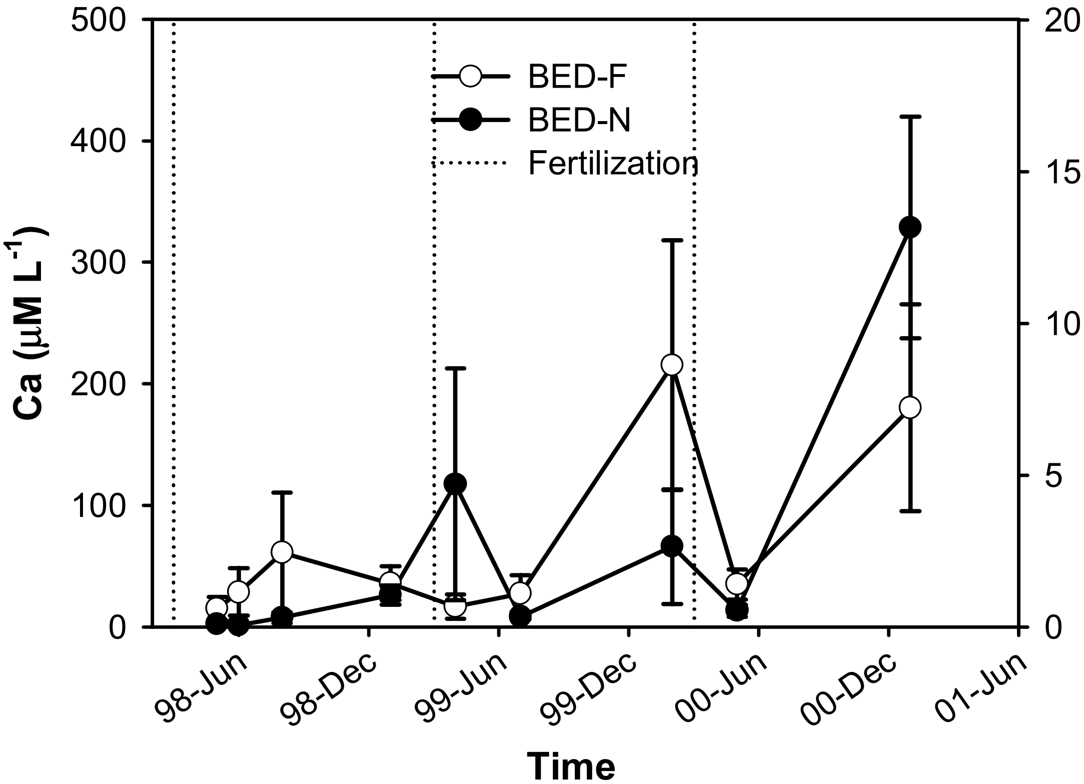

Figure 24. Mean calcium concentration in the soil solution from suction cup lysimeters installed at fragipan depth from different treatments: bedding control (BED-N) and bedding plus continuous fertilization (BED-F) on four sites planted in 1998 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

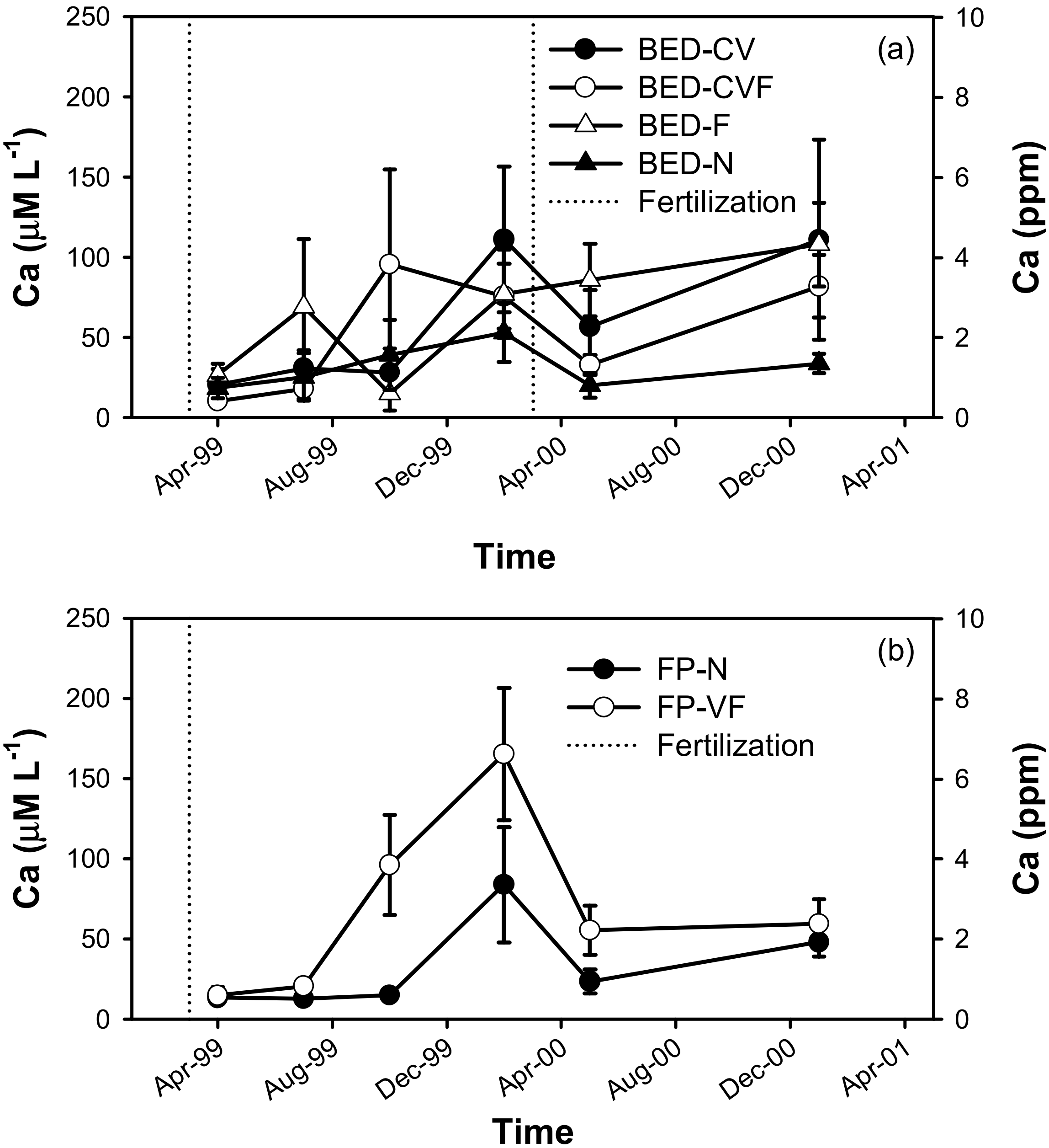

Figure 25. Mean calcium concentration in the soil solution from suction cup lysimeters installed at fragipan depth from four bedding treatments (a): bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF) and two flatplanting treatments (b): flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on six sites planted in 1999 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

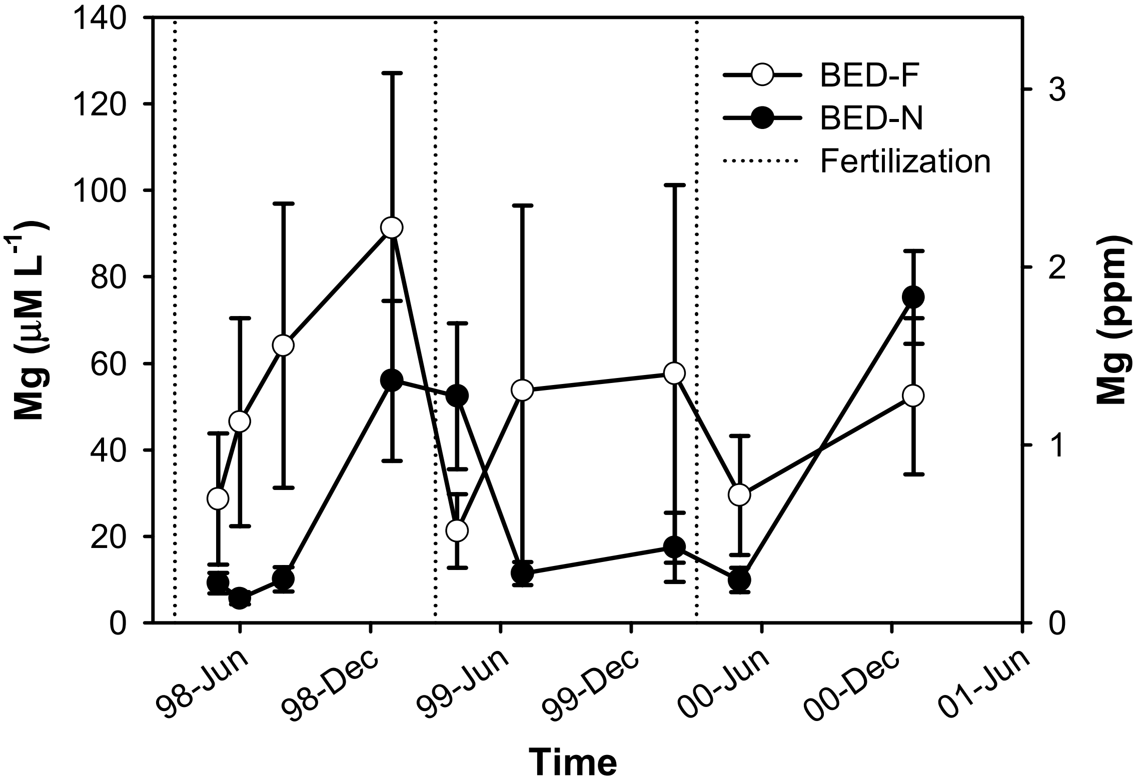

Figure 26. Mean magnesium concentration in the soil solution from suction cup lysimeters installed at fragipan depth from different treatments: bedding control (BED-N) and bedding plus continuous fertilization (BED-F) on four sites planted in 1998 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

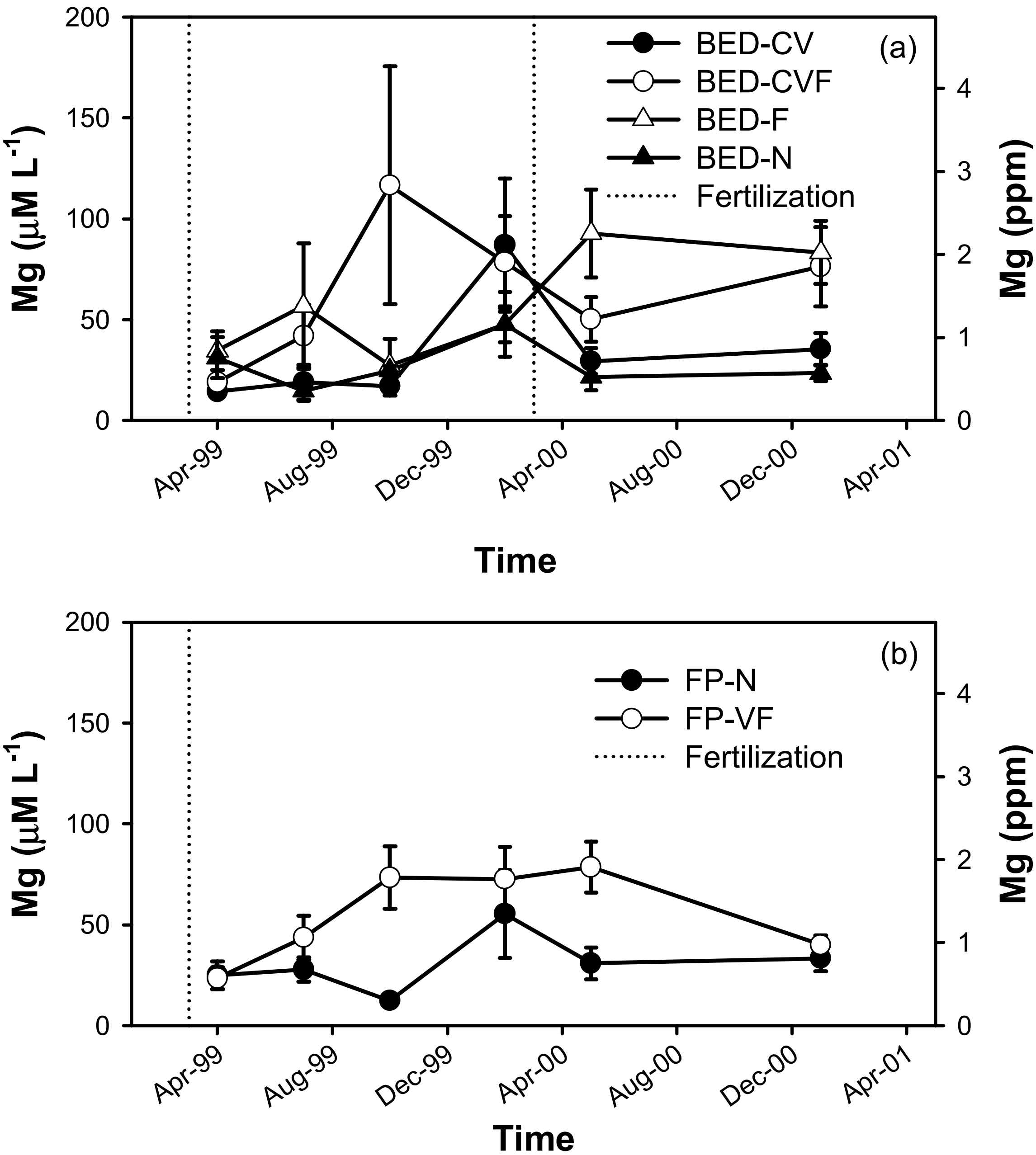

Figure 27. Mean magnesium concentration in the soil solution from suction cup lysimeters installed at fragipan depth from four bedding treatments (a): bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF) and two flatplanting treatments (b): flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on six sites planted in 1999 with loblolly pine in southern Arkansas. Vertical bars indicate one standard error.

Needle weight

Needle weight was not significantly affected by treatments on the 1998-sites, even though BED-F plots had consistently higher needle weight values after each growing season (Figure 28-f). Although needle weight did not differ significantly at the end of the first growing season on the 1999-sites, FERT seedlings had significantly higher needle weight than those of non-FERT plots after the second growing season in January, 2001 (Figure 29-f). Needle weights were significantly higher after the second growing season for all sites, compared to those after the first growing season. In the 1998 sites, needle weight was observed to increase non-significantly beyond the second growing season (Figure 28-f). Average needle weight for all treatments in the 1998 sites were 0.09, 0.13, and 0.15 gm in the Jan-99, Feb-00, and Jan-01 sampling sessions, respectively. These values were 0.09 and 0.12 gm in Feb-00 and Jan-01, respectively, for the 1999 site samples. Bedding significantly increased needle weight in the 1999 sites after the second growing season (Figure 29-f). Average needle weight for the BED seedlings was 0.12 gm compared to 0.10 gm for the FP seedlings during the 2001 sampling session.

Foliar N

Foliar N concentration was not affected by any treatment at any sampling session on any site. Nitrogen concentration for the BED-F seedlings in the 1999 sites after three years of fertilization was 1.17%, whereas that for BED-N was 1.42% (Figure 28-a) – perhaps a phenomenon that can best be explained by a dilution effect as unit fascicle weight was consistently higher for BED-F seedlings (Figure 28-f). Nitrogen concentration for the 1998 sites decreased significantly at the end of the second growing season which can again be explained by significant fascicle weight increase observed during this sampling session (Figure 28-f) and potential nutrient dilution. However, this was not observed for the

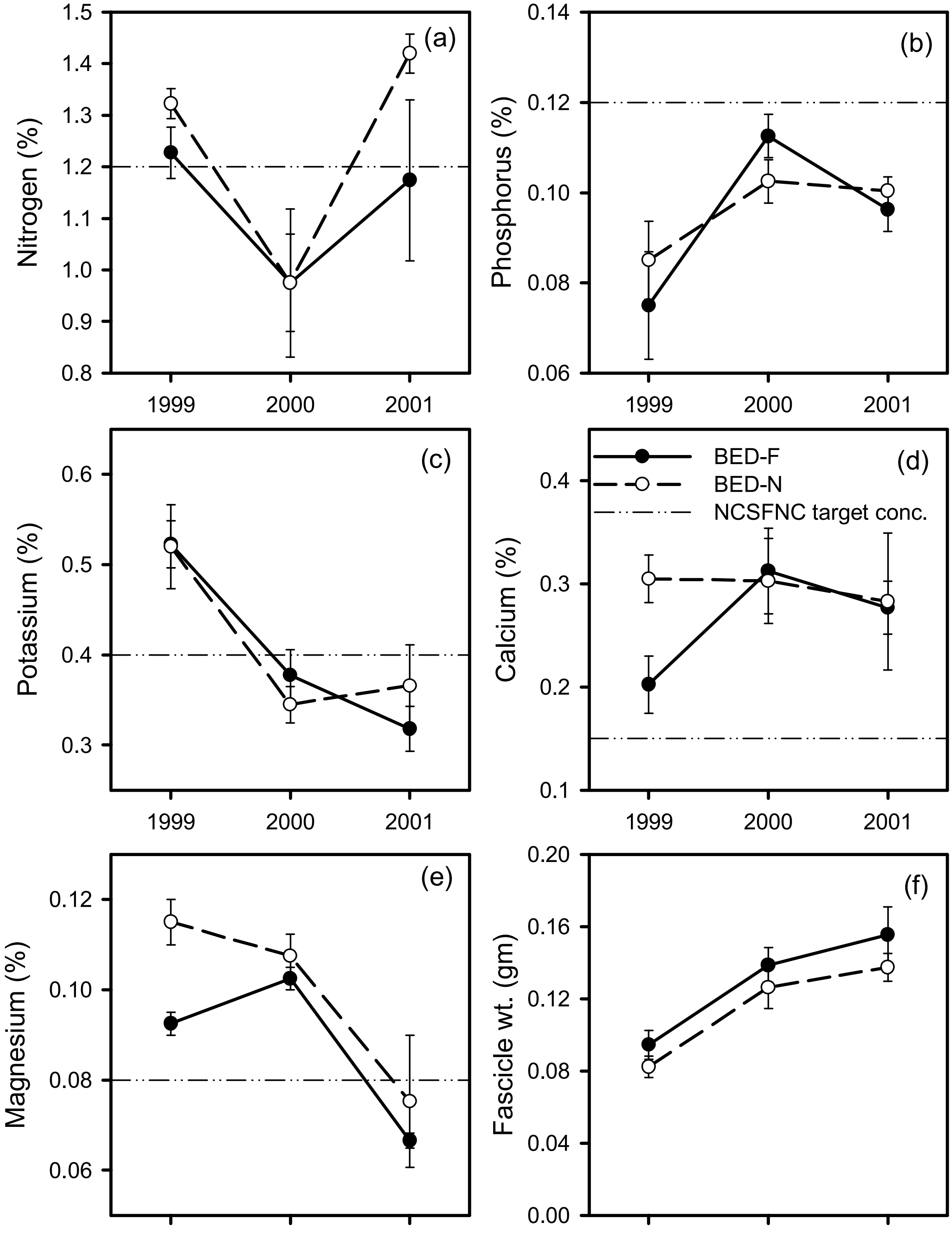

Figure 28. Needle nutrient concentrations and fascicle dry weight from different treatments: bedding control (BED-N) and bedding control plus continuous fertilization (BED-F) on four sites planted in 1998 with loblolly pines in southern Arkansas. Vertical bars indicate one standard error.

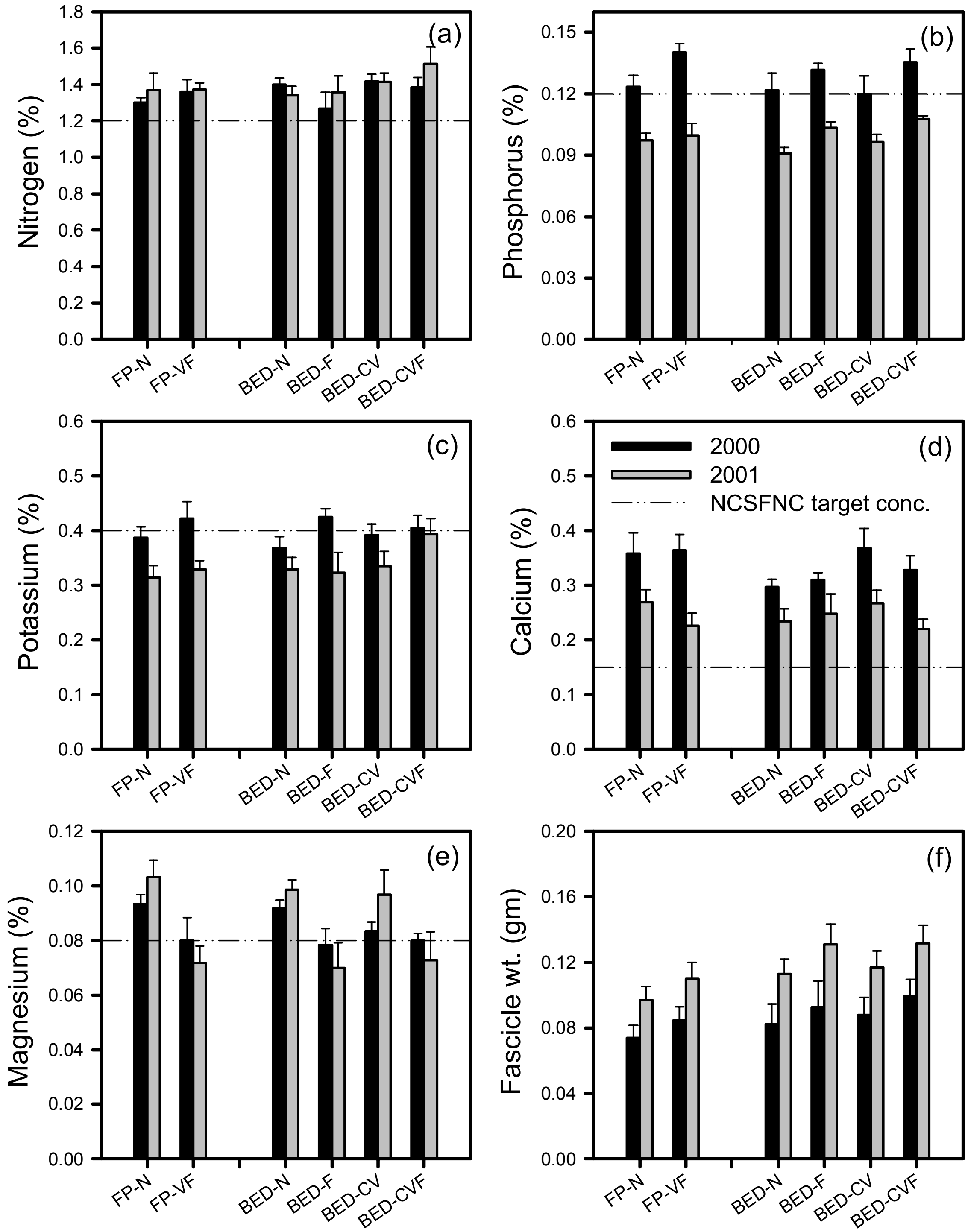

Figure 29. Needle nutrient concentrations and fascicle dry weight from different treatments: bedding control (BED-N), bedding plus continuous complete vegetation control (BED-CV), bedding plus continuous fertilization (BED-F), bedding plus continuous complete vegetation control and fertilization (BED-CVF), flatplanting control (FP-N), and flatplanting plus first-year fertilization and complete vegetation control (FP-VF) on six sites planted in 1999 with loblolly pines in southern Arkansas. Vertical bars indicate one standard error.

1999-site seedlings after their second growing season despite the fact that they also had significantly higher fascicle weight at the end of the second growing season than the first (Figures 29-a and f). Average seedling N concentrations during the Jan-01 sampling session for the FERT and non-FERT treatments on these sites were 1.34 and 1.37%, respectively.

Foliar P

Foliar P concentration was not affected by fertilization on the 1998 sites after three years of continuous fertilization (Figure 28-b). Although P concentration was significantly higher in the BED-F seedlings than those of BED-N for these sites at the end of second growing season, the difference was negligible (0.11% for BED-F vs. 0.10% for BED-N) and not present in the following year. Phosphorus concentration in the 1999 sites was not affected by treatments at any sampling session. However, the FERT treatment had significantly higher P concentration than the non-FERT at the end of each growing season. The FERT seedlings had on average 0.14% and 0.11% P in 2000 and 2001 growing seasons, respectively, compared to 0.11% and 0.10% for the non-FERT seedlings during the same sampling sessions, respectively. Regardless, P was found at a low concentration on all sites including BED-CVF and BED-F plots in the 1999 sites after two years of continuous fertilization, and BED-F plots in the 1998 sites after three years of continuous fertilization (Figures 28-b and 29-b). Soil phosphorus concentration in these sites was very low and ranged between 0.5 and 1.0 ppm (Table 1). Trees are more likely to respond to P fertilization where extractable soil P content is less than 3 ppm maximum (Schultz 1997). While it was expected that seedling response to P fertilization would be higher, Schultz (1997) also documented that under very poor drainage condition fertilization does not raise foliar P concentration, perhaps the phenomenon taking place for these sites.

Foliar K

Foliar K concentration was not affected by treatments in the 1998-sites after any growing season (Figure 28-c). Even though K concentration differences in the 1999-sites were non-significant among the treatments (Figure 29-c), the FERT treatments had a significantly increased needle K concentration in a linear contrast to the non-FERT treatments after the first growing season. Potassium concentration was highest after the first growing season in all sites and then decreased after each growing season possibly due to dilution by increased needle weight. High K mobility in plant tissues is perhaps why such a strong relationship between fascicle weight and K concentration was observed. In the 1998 sites, foliar K concentration, averaged for all seedlings, was 0.52%, 0.37% and 0.35% during the 1999, 2000 and 2001 sampling sessions, respectively, and in the 1999 sites, these values were 0.40% and 0.34% in the 2000 and 2001 sampling sessions, respectively.

Foliar Ca

Foliar Ca concentration in the 1998-site seedlings was not affected by treatment after three growing seasons. However, BED-N seedlings on these sites had significantly higher Ca concentration than those of BED-F after the first growing season (Figure 28-d). Calcium concentration was not affect by treatments in the 1999 sites during any sampling session. Foliar Ca concentrations for all treatments were high, well above the NCSFNC (North Carolina State Forest Nutrition Cooperative) target concentration (Figures 28-d and 29-d). Calcium concentrations for all treatments on the 1999 sites significantly decreased after the first growing season while those on the 1998 sites remained comparable.

Foliar Mg

Foliar Mg concentration in the 1998 sites was significantly lower for BED-F after the first growing season and comparable in the following years despite their lower values (Figure 28-e). In the 1999 sites, Mg concentration differed non-significantly in the first growing season, although seedlings of FERT treatments had a significantly lower Mg concentration than those of non-FERT treatments. However, after the second growing season during the 2001 sampling session, FERT seedlings had significantly lower Mg in their needles than the non-FERT seedlings (Figure 29-e).

The effect of fertilization on needle nutrients has been primarily on biomass growth and to a lesser extent on nutrient concentration. Fertilization resulted in 5% and 11.4% more height and GLD growth, respectively, and 12.8% more in fascicle weight for the 1998 sites after three years; and 15.6% and 24.6% more in height and GLD growth, respectively, and 13.9% more in fascicle weight for the 1999 sites after two years. Although no quantification has been done, foliage biomass was noticeably more vigorous in the fertilized plots compared to the non-fertilized plots. Tree growth has also been related to foliage biomass (Harrington et al. 2001).

Overall, nutrient concentrations for all seedlings have been low, especially phosphorus. This may be due to root hypoxia and the inability of the seedling root system to capture the applied nutrients at a desired potential. Reduction in root growth in loblolly pine due to soil inundation has been documented (DeBell et al. 1984, Lorio et al. 1972). Minirhizotron data show that new root initiation does not occur until late spring or early summer, perhaps the time when soil aeration increases, soil temperature begins to increase, and trees start to actively grow. In this study fertilization was done in March when all sites had standing water on them, thus at a time when roots were seen at minimum density and growth and rapid intake of nutrients is greatly reduced. Perhaps fertilization in the Western Gulf flatwoods should wait until early summer when plants start to actively grow and soil inundation disappears.

Conclusions

- Total N leaching loss following logging could be substantial on the Western Gulf flatwoods. Soil solution N concentration in this study was found as high as 14 ppm. This is independent of fertilization or mechanical site preparation.

- Phosphorus leaching was minimal, whereas basic cations were found in higher concentration in subsoil soil solution on fertilized plots.

- Fertilization effect on nutrient leaching was greater on the flatplanting plots than on the bedded plots.

- Fertilization did not increase needle nutrient concentration, but rather increased needle weight and thereby needle nutrient content.

- Concentrations of mobile basic cations (K and Mg) in needles decreased as needle weight increased, but remained deficient even after three years of continuous fertilization. Leaching loss of applied basic nutrients in addition to root inactivity at time of fertilizer application are considered the primary reasons.

- Needle P content was greater on the fertilized plot, but relatively low even after three years of continuous fertilization. The soils of the Western Gulf flatwoods are P deficient – but spring fertilization did not result in P supplement. Root inactivity due to root hypoxia is considered to be the primary reason. It is suggested that fertilization on these sites be delayed until early summer when there is no standing water and soil aeration is increasing with subsequent increases in root growth.

SUMMARY: HYPOTHESES EVALUATION

H: Mechanical site preparation will improve seedling growth and survival

At the end of the second growing season, seedlings planted on mechanically prepared plots had significantly greater height and goundline diameter than those with no mechanical site preparation. Average seedling height for mechanically prepared plots was 136.5 cm compared to 106.5 cm for those planted with no mechanical site preparation. Average groundline diameters were 22.8 and 19.5 mm, respectively. Although mechanical site preparation did not result in higher seedling survival across all sites, the effect was highly variable. Sites with apparently poor drainage showed higher survival gain from mechanical site preparation.

H: Chemical vegetation control will improve seedling water relations by means of increased soil water availability and therefore increase growth and survival

Chemical vegetation control increased soil water availability which resulted in higher seedling water potential. The effect was highlighted during the late summer when water was more limiting than during the early summer. Although these improved water relations resulted in increased seedling growth, there was no observed effect on survival.

H: Fertilization will increase growth by means of adding available nutrients to seedlings

Fertilization increased total nutrient accumulation in seedlings by means of increasing needle weight. Although no measurement was taken to actually quantify seedling foliage biomass, fertilized seedlings visibly appeared to have more needles. Fertilization resulted in significantly more above-ground growth at the end of all growing seasons on all sites.

H: Fertilization will enhance soil nutrient leaching loss

Suction cup lysimeters were inserted to the restrictive layer. There were significantly more basic cationic nutrients in the lysimeter soil solutions from fertilized plots than those from non-fertilized plots. However, fertilization did not result in enhanced nitrogen or phosphorus concentrations in the lysimeter soil solutions. It was assumed that nutrients that reached the restrictive layer were ultimately lost from the site, perhaps through horizontal flow.

H: Fertilization will enhance root growth

Seedlings on fertilized plots had higher seedling root growth than did those in the controls. There was 21% more root length on the fertilized trees compared to the control trees.

H: Fertilization alone will increase competition resulting in less soil water availability at time of seedling water stress and subsequent lower seedling water potential

There was visibly more interspecific competition in the fertilized plots compared to the control plots – although no such quantification was done. No significant change in volumetric soil moisture content or seedling water potential was detected due to fertilization. However, fertilized plots had the lowest (not significant) water potential in both growing seasons. In addition, seedlings on fertilized plots ceased stomatal conductance prior to those on control plot during the August 2000 sampling session, the only occasion such a phenomenon was observed.

H: Fertilizer and herbicide application will have be an additive effect on growth

Growth from fertilizer and herbicide as a combined treatment exceeded the summation of the independent effects of fertilizer and herbicide.

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APPENDIX: Table showing sites established in 1998 and 1999

Year Established	Company	Site Name	Site Code	Taxonomic Class	Depth to Fragipan or Argillic (cm)
1998	International Paper	Garrett Road	IP1	Fine-silty, siliceous, semiactive, thermic Typic Endoaquults	20
	International Paper	Sloan Road	IP2	Fine-silty, siliceous, semiactive, thermic Typic Endoaquults	25
	Plum Creek Timber Company	Airport Road	PC1	Fine-silty, mixed, active, thermic Aquic Fragiudalfs	42
	Plum Creek Timber Company	Yale Camp Road	PC2	Fine-silty, mixed, active, thermic Aquic Fragiudalfs	23
1999	International Paper	Plantation Road	IP3	Fine-silty, siliceous, semiactive, thermic Typic Endoaquults	65
	Plum Creek Timber Company	Braska Johnson Road	PC3	Fine-silty, mixed, active, thermic Aquic Fragiudalfs	35
	Potlatch Corporation	Deer Stand	PL1	Fine-silty, siliceous, thermic Typic Glossaqualfs	40
	Potlatch Corporation	Artesian	PL2	Fine-silty, siliceous, thermic Typic Glossaqualfs	28
	Potlatch Corporation	Stanley	PL3	Fine-silty, siliceous, thermic Typic Glossaqualfs	50
	Potlatch Corporation	Sam Colvin Tram	PL4	Fine-silty, siliceous, thermic Typic Glossaqualfs	60

VITA

Mohd Shafiqur Rahman was born on November 30, 1970 in Dhaka, Bangladesh. He is the third of four children from Shamsur Rahman and Monira Rahman. He finished his high school education in Dhaka and went to Chittagong for his undergraduate program in Forestry at the Institute of Forestry, Chittagong University. Following graduation, Mohd Rahman came to Texas A&M University for a Master's program in January, 1994. He completed his Master's in the spring of 1997 and went back to his hometown in Dhaka, Bangladesh. Mohd Rahman came back to Texas A&M University for his Ph.D. program in the summer of 1998. He is currently employed with the Department of Forest Science at Texas A&M University as a Research Associate.

Mohd Rahman is married to Sadaf Monam and is blessed with a daughter, Sabahat Rahman. His current address is: 2904-C Silver Spur Cir, Bryan, TX 77801-1751, USA.